

THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

**Fatigue assessment of container ships –
a contribution to direct calculation procedures**

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Abstract

Within the field of marine structural engineering, the introduction of new materials and material classes, the development of production techniques and new design, and new requirements imposed by authorities are examples which justify a need for continuous revisit and update of fatigue assessment methodologies of marine structures. This thesis contributes to the development and improvement of fatigue assessment methodology for ship structures. Although the work is demonstrated using container vessels here, the methodology provides good insight into the direct calculation procedure of fatigue in general.

A practical time-domain procedure is proposed that utilises more sophisticated numerical tools to take account for realistic sea conditions and actual operational profiles in the direct calculation of fatigue damage in ship structures. The feasibility and sensitivity of this time-domain procedure were investigated through case studies. In-depth studies are presented for nonlinear wave loads and their influence on fatigue damage estimation in the deck, bilge, and side-shell structures of container ships. The proposed time-domain procedure provides reasonable and conservative fatigue life estimations in comparison with the fatigue methodologies in widespread use.

A method is proposed to derive local stress for fatigue calculation from the ship's global nominal stress. The idea behind this method is that a stress concentration factor should be based on realistic loadings. This method utilises stress ranges extracted from the stress history, which is particularly suitable for time-domain fatigue analyses. Nonlinear finite element (FE) analyses are carried out to investigate the cyclic material response during severe wave loading conditions. The results indicate that the amount of accumulated plastic strain is often low and that the material exhibits an elastic shakedown response after repeated cyclic loadings. It was therefore concluded that elastic FE analyses followed by stress-based fatigue assessments can be successfully employed, at least for the studied cases.

Furthermore, important influencing factors causing uncertainties in fatigue analyses are identified and quantified by comparing fatigue damages estimated using various numerical methods. Uncertainties connected with the wave environment are also studied through the comparison of fatigue assessment using different wave descriptions for a specific sea condition and different distributions of the long-term wave environment.

In addition, concerning that the girder stresses occur as a combination of torsion, horizontal and vertical bending moment loadings, an analytical derivation for the separation of wave-induced girder stresses is presented. As a result, it was possible to identify the contribution to fatigue damage, in various locations of containership structures, from stress components that are caused by these different loading modes. The practical usefulness of the results is demonstrated in an example of ship fatigue routing between Europe and North America.

Keywords: container ship, fatigue, finite element analysis, full-scale measurement, nonlinear panel method, ship routing, side-shell structures, stress concentration, time-domain method, warping stress.

Preface

This thesis is comprised of work carried out during the years 2008-2013 at the Division of Marine Design (former Ship Design between 2008 and 2011), Department of Shipping and Marine Technology, Chalmers University of Technology. The work was funded by VINNOVA, the Swedish Governmental Agency for Innovation Systems, and by LIGHTHOUSE, the Swedish Competence Centre in Maritime Education and Research (www.lighthouse.nu).

First and foremost, I would like to thank my supervisor Professor Jonas Ringsberg for his deeply dedicated support and infectious enthusiasm, as well as for his patience, encouragement and friendly care, which have been very important for the outcome of this work. I would also like to thank my co-supervisors, Adjunct Professor Erland Johnson and Professor Igor Rychlik, for many insightful and inspiring discussions. Grateful thanks are forwarded Gaute Storhaug Ph.D. at Det Norske Veritas in Høvik, Norway, for initiating the ship routing project and for sharing his expertise in maritime industry. Specially, I would like to thank Wengang Mao Ph.D., for collaboration during the years, for open discussion and constructive criticism and for, in the dark winter days, sharing topics besides cracking and damage.

I also would like to express my gratitude to persons who have been resources of knowledge and inspiration, in particular: Louise Ulstein at Det Norske Veritas for kind support in application of the SESAM software package; Emeritus Professor Anders Ulfvarson and Jan Bergholtz at Kattagatt Design AB for sharing their broad knowledge in naval architecture; Giorgio Contento at the University of Trieste, Italy and Kaijia Han at Det Norske Veritas for sharing their experience in hydrodynamic simulation; and Heikki Remes at Aalto University, Finland for changing ideas in fatigue research.

In addition, I would like to thank my colleagues at the Department of Shipping and Marine Technology, for providing an amiable working and social environment and for all the fruitful and inspiring discussions over the years.

This thesis is dedicated to my wife, Annie, my daughters, Johanna and Sandra, and my parents. Your love is the motivation when I pursue my Ph.D.

Zhiyuan Li
Gothenburg, August 2013

List of appended papers

- Paper A** Li, Z., Ringsberg, J. W. (2012). *Fatigue routing of container ships – assessment of contributions to fatigue damage from wave-induced torsion and horizontal and vertical bending*. Ships and Offshore Structures, **7**(2): 119-131.
- Paper B** Mao, W., Li, Z., Ringsberg, J. W., Rychlik, I. (2012). *Application of a ship-routeing fatigue model to case studies of 2800 TEU and 4400 TEU container vessels*. Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment, **226**(3): 222-234.
- Paper C** Li, Z., Ringsberg, J. W., Storhaug, G. (2013). *Time-domain fatigue assessment of ship side-shell structures*. International Journal of Fatigue, **55**(1): 276-290.
- Paper D** Li, Z., Mao, W., Ringsberg, J. W., Johnson, E., Storhaug, G. (2013). *A comparative study of fatigue assessment of container ship structures using various direct calculation approaches*. Submitted for publication in Ocean Engineering.
- Paper E** Ringsberg, J. W., Li, Z., Tesanovic, A., Knifund, C. (2013). *Linear and nonlinear FE analyses of a container vessel in harsh sea state*. Submitted for publication in Ships and Offshore Structures.

List of additional peer-reviewed scientific publications

The author of this thesis is the co-author of the following peer-reviewed conference and journal articles:

Li, Z., Ringsberg, J. W., Mao, W. (2010). *Fatigue damage assessment of container ships concerning wave-induced torsion*. Proceedings of the ASME 29th International Conference on Ocean, Offshore and Arctic Engineering (OMAE 2010). Shanghai, China. June 7-11, 2010. (Presenting author).

Mao, W., Li, Z., Galtier, T., Ringsberg, J. W., Rychlik, I. (2010). *Estimation of wave loading induced fatigue accumulation and extreme response of a container ship in severe seas*. Proceedings of the ASME 29th International Conference on Ocean, Offshore and Arctic Engineering (OMAE 2010). Shanghai, China. June 7-11, 2010.

Li, Z., Ringsberg, J. W. (2011). *Direct calculation of fatigue damage of ship structure details*. Proceedings of the ASME Thirtieth International Conference on Ocean, Offshore and Arctic Engineering (OMAE 2011). Rotterdam, the Netherlands, June 19-24, 2011. (Presenting author).

Mao, W., Ringsberg, J. W., Li, Z., Rychlik, I. (2011). *Assessment of full-scale measurements with regard to extreme hogging and sagging condition of container ships*. Proceedings of the ASME Thirtieth International Conference on Ocean, Offshore and Arctic Engineering (OMAE 2011). Rotterdam, the Netherlands, June 19-24, 2011.

Li, Z., Ringsberg, J. W., Mao, W. (2012). *A comparison of direct calculation approaches applied on the fatigue strength assessment of a Panamax container ship*. Proceedings of the ASME Thirty-first International Conference on Ocean, Offshore and Arctic Engineering (OMAE 2012). Rio de Janeiro, Brazil. July 1-6, 2012. (Presenting author).

Mao, W., Li, Z., Ringsberg, J. W., Rychlik, I. (2012). *Fatigue variation in ships due to the variability of environmental loads*. Proceedings of the ASME Thirty-first International Conference on Ocean, Offshore and Arctic Engineering (OMAE 2012). Rio de Janeiro, Brazil. July 1-6, 2012.

Li, Z., Mao, W., Ringsberg, J. W., Johnson, E., Storhaug, G. (2012). *A comparative study of fatigue assessment of a container ship structure using various direct calculation approaches*. Proceedings of the International Conference on Maritime Technology (ICMT2012). Harbin, China. June 26-28, 2012. (Presenting author).

Mao, W., Ringsberg, J. W., Rychlik, I., Li, Z. (2012). *Theoretical development and validation of a fatigue model for ship routing*. Ships and Offshore Structures, 7(4): 399-415.

Ogeman, V., Li, Z., Mao, W., Ringsberg, J. W. (2013). *A matrix-based method including bending and torsion and their impact on fatigue assessment of container ships*. (In process).

Contributions to appended papers

The papers presented in this thesis were prepared in collaboration with co-authors. The contributions by the author to the papers are summarised below.

- Paper A** Contributed to the ideas presented, planned the paper with the co-author, carried out the numerical simulations and wrote the manuscript with the co-author.
- Paper B** Contributed to some of the ideas presented, took part in the planning of the paper, carried out parts of the fatigue polar diagram calculations and wrote parts of the manuscript.
- Paper C** Contributed to the ideas presented, proposed the new local stress factor, was responsible for the planning of the paper, carried out the numerical simulations and wrote most of the manuscript.
- Paper D** Contributed to the ideas presented, was responsible for the planning of the paper, carried out the comparative study of fatigue damage and wrote most of the manuscript.
- Paper E** Contributed to the ideas presented, took part in the planning of the paper, carried out parts of the time-domain fatigue analyses and wrote parts of the manuscript.

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1 Introduction

This chapter presents the background and motivation of the thesis. It includes a brief description of the trends, challenges, and importance of container shipping. The objectives of the thesis are then presented, followed by discussions of the scope and limitations of the thesis. The thesis is then outlined.

1.1 Background and motivation

Ships and offshore structures are physically large structures that are subjected to various environmental (wind and waves) and internal (cargo and ballast water) loads. These structures are also exposed to environmental factors that affect their long-term usage and designs, including corrosive sea water and large variations in operating temperature (high temperatures near the Equator and very low temperatures in the Arctic). These environmental loads and factors underscore the complexity in the structural design and dimensioning of marine structures.

The International Ship and Offshore Structures Committee (ISSC) is a forum for the exchange of expert information in undertaking and applying marine structural research. Since 1961, the ISSC has arranged a triennial congress to communicate and discuss the latest knowledge and understanding in the various disciplines underpinning marine structural design, production, and operation through internationally collaborative endeavours. The ISSC is divided into a number of technical committees, where committee structures and mandates have clear connections designating limit states, often with an overlap of mutual interest between them.

The safe and reliable design of marine structures follows rules, guidelines, and recommendations from classification societies. The design methodology considers four categories of limit state designs that include a structure's functionality, ultimate strength, long-term usage, and survivability in case of accidents or rare load events (ISSC, 2009):

- serviceability limit state (SLS),
- ultimate limit state (ULS),
- fatigue limit state (FLS), and
- accidental limit state (ALS) designs.

The need for continuous revisiting and updating of marine structure fatigue assessment methodologies can be motivated by the development and introduction of new materials or material classes, new/existing production techniques, new types of marine structures (or the re-design of existing ones), and new requirements and demands on structures and their usage. Such developments have been realised at the ISSC, where the interest and concern for fatigue and FLS are considered among various technical committees, including Environment (I.1), Loads (I.2), Quasi-Static Response (II.1), Dynamic Response (II.2), Fatigue and Fracture (III.2), Design Principles and Criteria (IV.1), Design Methods (IV.2), and Material Fabrication and Technology (V.3)—see ISSC (2012). Accordingly, this thesis emphasises a structural analysis based on the FLS design, with a focus on ship structures. Further motivations for scientific study are briefly noted below:

Safety and loss of property: Fatigue damage in ship structures can have severe consequences. If fatigue cracks are not detected and repaired in time, they can contribute to the structural failure of an entire hull girder. The MSC Carla accident in 1997 highlights the possible consequences of such failures; fatigue cracking and welding repairs were found in the fractured hull (SSC, 1985), although the detrimental influence of the fatigue to the hull strength still needs to be clarified. More recently, the container ship MOL Comfort fractured during inclement weather in the Indian Ocean on 17 June 2013 and eventually sank. This incident is currently under investigation, and fatigue cracking is one of the suspected causes that contribute to the structural failure (according to private correspondence with the flag authority).

Environmental consequences and economic costs: Fatigue damage and ship structural failures may not directly result in catastrophic structural failures, but they can pose a risk for environment and are related to economic costs. According to DNV (2013a), fatigue cracks are the most common damage occurring on ships and may cause oil spills into ballast water or the sea, though oil leakage due to fatigue cracking does not typically result in catastrophic environmental consequences. However, the negative impact on the maritime environment should not be ignored; the economic costs of maintenance and downtime can be substantial because fatigue cracks are typically addressed by local repairs.

Development of new construction materials and their utilisation: High-tensile steel was first introduced to the ship-building industry in the 1980s, with steel grades as high as 470 MPa recently approved by classification societies (see DNV (2011)). With the introduction of high-tensile steel in hull structures (initially in decks and bottoms for hull girder strength and then in local structures), fatigue problems have become more prevalent. The goal-based design philosophies already in use will continue to be implemented in ship design processes. The use of such philosophies will enable the choice of a variety of construction materials, such as steel, aluminium, and composite materials. Therefore, material science and fatigue-driven research will always be relevant.

Transport efficiency - lightweight design and fuel consumption: The shipping industry strives to create more lightweight ship structures to minimise fuel consumption. The introduction of the Energy Efficiency Design Index (EEDI) and transport efficiency (IMO, 2011)—for example, a high ratio of payload to fuel consumption—as mandatory technical measures has driven holistic analyses of energy savings and maximised transport work. Thus, structural integrity analyses should be continuously revisited and updated to ensure safety targets.

Dimensions of ship structures continue to increase: The development of ship size in many shipping segments is increasing, particularly for container vessels; this increase in ship size is further addressed in Section 1.2. The prescriptive work rule has largely been used to design and predict the structural integrity of these new vessels. However, to what extent can these rules be applied without major revisions? In contrast to normal wave-induced loads, such phenomena as whipping, springing, and bow/aft slamming loads may now play a more important role, even if they have little influence on the fatigue damage accumulation loads for smaller ships.

With today's development of advanced computational tools and computer capacities, it should be possible to reliably estimate the long-term usage of ship structures and their intervals for inspection and maintenance. The aforementioned examples, which relate to FLS design,

demonstrate that rational and reliable methods for long-term usage and maintenance planning must be developed. Consequently, the motivation for this thesis is to contribute to the development of fatigue assessment methods for ship structures, with an emphasis on container vessels.

1.2 Container ships

Container ships are becoming increasingly important in the shipping industry. As manufactured goods are increasingly containerised, the container ship fleet has expanded its share from 1.6% of the world fleet in 1980 to over 13% (in tonnage) in 2011 (UNCTAD, 2012); this trend is expected to continue. The role of container ships in global trade is even more important than this tonnage share would suggest: 52% of today's seaborne trade (in terms of dollars) is containerised (UNCTAD, 2012).

Container ship size has dramatically increased due to economics of scale. Since the emergence of the first container ship in the mid-1950s, five (major) generations of container ships have been developed, increasing the container transport capacity from less than 1,000 TEU (TEU=the 20-foot equivalent unit) to 18,000 TEU—see Fig. 1.1 (Rodrigue, 2013). It is expected that the size of container ships will continue to increase because of the driving force of scale economics (Rodrigue, 2013). New and more sophisticated design methodologies and container ship operations will be necessary to keep up with this rapid development. The work presented in the thesis will focus on container ships due to the motivations outlined in Section 1.1, the importance of container shipping for the global economy, and the rapid development of this type of vessel.

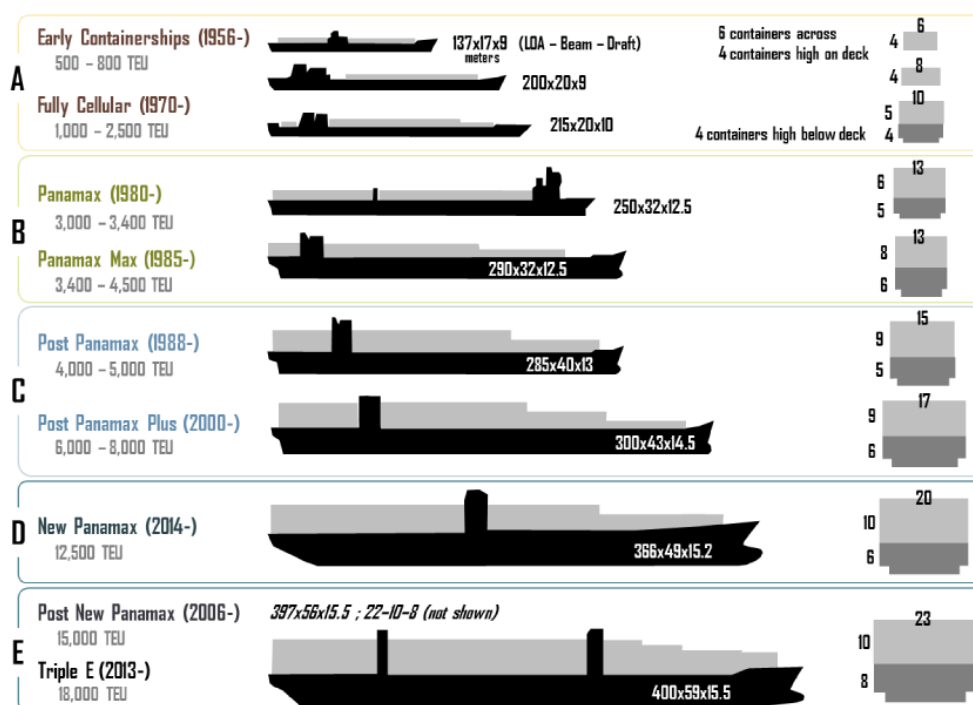


Fig. 1.1: The evolution of container ships (from Rodrigue (2013)).

Compared to other major types of commercial vessels (i.e., bulk carriers and oil tankers), container ships are unique in many respects. First, container ships have U-shaped cross-sections to maximise load capacity and enable efficient container loading and unloading. Second, container vessels are characterised by a flat overhanging stern and pronounced bow

flare; the local bow flare angle of a modern large container ship can reach 61° (Storhaug and Heggelund, 2008). These hull shapes make them more susceptible to torsion-induced and slamming loads. In addition, container ships typically operate at a higher speed than other large commercial vessels. The average service speed of container ships ranges from 21 to 25 knots, whereas oil tankers range from 12 to 13 knots and bulk carriers range from 10.5 to 14.5 knots (UNCTAD, 2012). A higher service speed implies more wave loads during the same reference time period, leading to more fatigue load cycles.

Until recently, fatigue cracks on container vessels have not been largely reported in the public literature. This can be partially explained by the fact that the container fleet is relatively young, with an average age per ship of 10.7 years, compared to bulk carriers (15.3 years), oil tankers (16.4 years), general cargo ships (24.2 years), and other types of ships (25.1 years)—see the description in UNCTAD (2012). However, fatigue problems do exist for container vessels. Side-shell fatigue cracks were reported by Fricke et al. (2010), and it was found that a growing number of fatigue cracks occurred at the intersections of longitudinals and transverse webs in 10-year-old Panamax container ships, as shown in Fig. 1.2a. Serious deck cracks were discovered in container vessels after less than eight years of service, as indicated by Storhaug and Moe (2007)—see Fig. 1.2b for an example. A survey indicated that the structural design followed all regulations and good welding workmanship was observed at the cracked joints. These findings justify the need for fatigue assessments of individual vessels under actual operating conditions, using more sophisticated approaches with respect to wave loading representation and fatigue stress analyses.

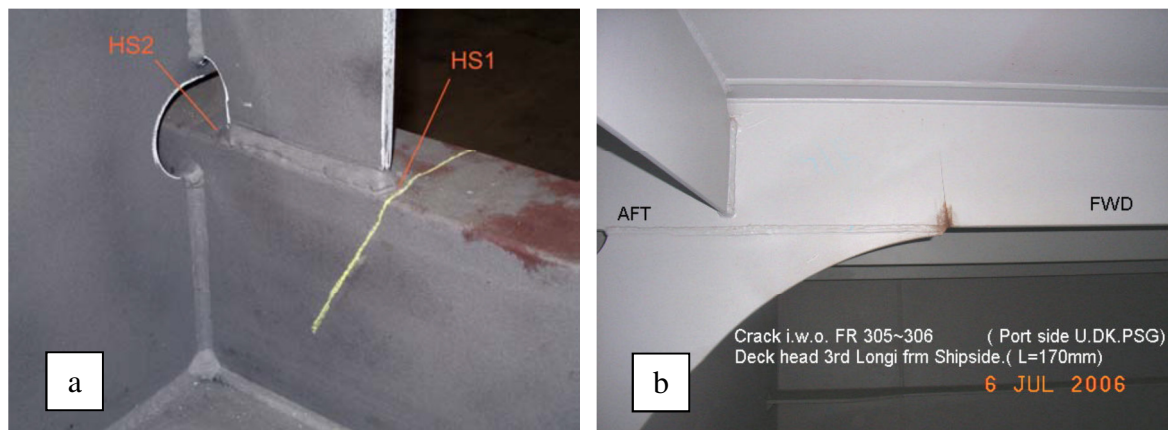


Fig. 1.2: (a) Fatigue crack at the side longitudinal of a Panamax container vessel (from Fricke et al. (2010)); (b) Crack in deck longitudinal at forward quarter length of another Panamax container ship (from Storhaug and Moe (2007)).

The accuracy of different fatigue assessment methodologies of ship structural details was investigated in a comparative study by Fricke et al. (2002). Fatigue assessment procedures proposed by eight major classification societies were compared in a case study of the pad detail on the longitudinal coaming of a Panamax container vessel. The results indicated that the predicted fatigue life varied significantly. The study emphasises the need for appropriate design tools to achieve reliable fatigue life predictions.

Most of the current classification rules and guidelines are applied to general ship types without considering a vessel's specific hull shape and intended operation. Although the International Association of Classification Societies (IACS) has published common structural rules for bulk carriers (CSR-B (IACS, 2009)) and oil tankers (CSR-T (IACS, 2008)), the rule

separation between the CSR-B and CSR-T is due to different preferences in the procedural analyses of the classification societies instead of the differences in hull shapes or operational profiles. Classification societies have recently reached a new agreement on harmonised common structural rules for both bulk carriers and oil tankers (CSR-H (IACS, 2013)) that will be enforced in the near future. In the CSR-H, the strength analysis methodology is unified (to a great extent) for both ship types.

As for container vessels, there is no applicable common structural rule. Different classification societies have created their own rules and guidelines for the strength and fatigue analyses of container ships; see for example, BV (2008a), DNV (2009a) and GL (2007). The fatigue assessment procedures described in these references are similar and based on either the rule load method or spectral method or both (see Section 2.3).

1.3 Objectives

The overall objective of this thesis is to contribute to the development and improvement of a stress-based fatigue assessment methodology for ship structures. The work aims to establish a methodological framework that utilises more sophisticated numerical tools in the direct calculation of fatigue damage in ship structures, with an emphasis on container ships. It should be possible to simulate and evaluate the accumulated fatigue damage on specific ship routes. Essential influencing factors of fatigue life prediction will be evaluated through a comparative study of various fatigue analysis methods to better understand the uncertainties associated with fatigue damage calculation. The overall objective will be achieved through the following subtasks:

- To propose a practical time-domain procedure for ship fatigue assessment that contributes to enhanced accuracy in fatigue life predictions.
 - Validate time-domain numerical results by comparing with results from methods that are in widespread use and referencing full-scale measurements performed on case study vessels.
 - Assess the feasibility and sensitivity of the time-domain fatigue assessment procedure through case studies of container vessels in the North Atlantic trade.
 - Evaluate the impact of nonlinear wave loads in the fatigue damages of longitudinal structural members in the decks and side-shells of container ships.
 - Examine the realistic local stress in hotspots with the time-domain methodology. Establish a procedure for determining the stress concentration; this procedure would be particularly useful for fatigue damage calculations.
 - In harsh sea states, the local stress in structural details can exceed the yield stress. Investigate (through nonlinear finite element (FE) analyses) the amount of accumulated plastic strain during repeated loading conditions and the cyclic material responses. Assess whether a strain-based fatigue methodology should be used over the most often-used stress-based approaches.

- To evaluate the influencing factors in fatigue damage calculation procedures.
 - Study the measurement and model uncertainties related to sources that measure the wave environment (and the model uncertainties in the description of different wave models) to quantify their influence on fatigue life predictions.
 - Compare various numerical methods in different steps (i.e., the strip theory code versus the panel method code in hydrodynamic simulation, the FE method versus beam theory in the determination of fatigue stress, and time-domain cycle counting versus the frequency-domain spectral approach) in fatigue damage calculations.
 - Identify and quantify the uncertainties associated with various approaches for deriving stress concentration relationships.
 - Through the application of ship fatigue routing, demonstrate that the fatigue life of individual vessels depends largely on their operational profiles and the sea conditions actually encountered.
- To quantify the contribution of torsional, horizontal, and vertical bending moments to the fatigue damage accumulation in the hulls of container ships.
 - Develop a methodology for longitudinal normal stress components that refers to wave-induced torsional, horizontal, and vertical bending moments, respectively.
 - Quantify the degree to which (and during which heading conditions) each of these stress components contribute to the total fatigue damage for selected locations in the container ship structure. Contribute to further development of an existing ship fatigue routing model by including the partial fatigue damage that refers to torsion-induced fatigue damage (i.e., from warping-induced stresses).

The objectives of this work fit well with the vision of the Chalmers University of Technology—to contribute to sustainable development by working with challenges related to our environment, social equity, and economic welfare and demands. In this thesis, the fatigue assessment of container vessels is presented with the objective of contributing to the enhanced reliability of fatigue life predictions for these structures. Therefore, the work addresses two of the three challenges: environmental and economic demands (see Section 1.1 for examples and motivation).

1.4 Focus and limitations

Fatigue assessment is a process of comparing fatigue loads with fatigue strength, although the borderline in between is not always distinct. This thesis focuses on fatigue loads, whereas fatigue strength is left largely untouched.

This investigation concentrates on specific structural parts, namely, the longitudinals in the deck, sides, and bottom. Side and bottom longitudinals are investigated because they are of complex geometrical configurations and subjected to complex loadings. Deck longitudinals have also been selected for an in-depth investigation because the stresses at deck level are typically large and in tension, and thus, structural details in this region must be carefully considered; significant cracks have been found in the deck regions of one of the case study container vessels. These locations also allow numerical simulations to be compared with full-scale measurements of the specific case study ships of these types of structural members.

However, hatch corners are not studied in this investigation although they are regarded as a crucial design consideration. The cracking of container ship hatch corners has been a well-recognised problem since the advent of container ship design. The existing literature has provided well-documented case histories of fatigue cracking of hatch corners in container

ships; see for example Chiou and Chen (1985). Detailed analysis procedures can be found in the guidance provided by classification societies; see for example, ClassNK (2003) and DNV (2009a). Due attention has been paid to this problem, and it will not be further investigated here.

There are other issues important to ship fatigue assessment that are excluded from the scope of this thesis. The first relates to wave-induced vibration. A ship is typically considered a rigid body in the hydrodynamic and structural analyses that are performed to determine the deflection and stress in a structure. In reality, however, a ship is flexible and may vibrate. Springing and whipping are two important wave-induced vibrations that must be considered with respect to fatigue damage. Various opinions exist regarding the contribution of springing and whipping to overall fatigue. Some researchers maintain that wave-induced vibrations significantly contribute to total fatigue damage (see, e.g., Drummen et al. (2008), Mao (2010), Gu and Moan (2002), and Storhaug et al. (2007)). Due to the complexity of vibration effects, this topic is excluded, thus representing a limitation of the current work.

Another limitation is related to ship draught and loading conditions. In general, container ships operate under three loading conditions: fully loaded, empty-container, and ballast conditions, although a container ship is seldom sailing in a ballast condition or with empty containers due to economic considerations in real life. Theoretically, the dynamic wave loading on the hull varies with the draught and loading distribution, and any fatigue damage received at the hull differs under various loading conditions. Thus, it is beneficial to consider more than one loading condition in the fatigue evaluation. In this thesis, however, fatigue damage calculations are only carried out for the fully loaded condition.

Other limitations are described as follows: (1) Dynamic internal tank pressure from ballast water resulting from ship motions are not considered within the scope of this thesis. However, this dynamic pressure is expected to contribute to fatigue damage in the local tank structures. (2) In structural analyses, the stress range is obtained from the computation of hotspot stresses by assuming potential fatigue cracking from the weld toe. This approach is incomplete because in reality, fatigue cracks may also initiate in the weld root. (3) The S-N curve methodology utilised in the scope of this thesis is generally applied in the prediction of the crack initiation life, which implies that the proposed procedure is in principle applicable for new ships and cannot be used for predicting residual fatigue life for cracked vessels already in operation.

1.5 Outline of the thesis

Chapter 2 presents the relationships between appended papers, in addition to individual summaries of these papers. The numerical methods and tools are also listed in Chapter 2. Chapter 3 presents an overview of the methodologies commonly accepted for fatigue assessment. The methodology used in this thesis is also highlighted. The case study vessels are described in Chapter 4. In Chapters 5 through 7, the work performed and the scientific contributions in this thesis are presented as individual sub-fields. Finally, conclusions and ideas for future work are presented in Chapters 8 and 9, respectively.

2 Summary of appended papers

This thesis contains a brief summary of five appended papers—Papers A through E. The purpose of this summary is to present an overview of the papers and place their scientific work and contributions in a wider context according to the aims and objectives of this thesis. Figure 2.1 presents a schematic overview of the relationships between Papers A through E.

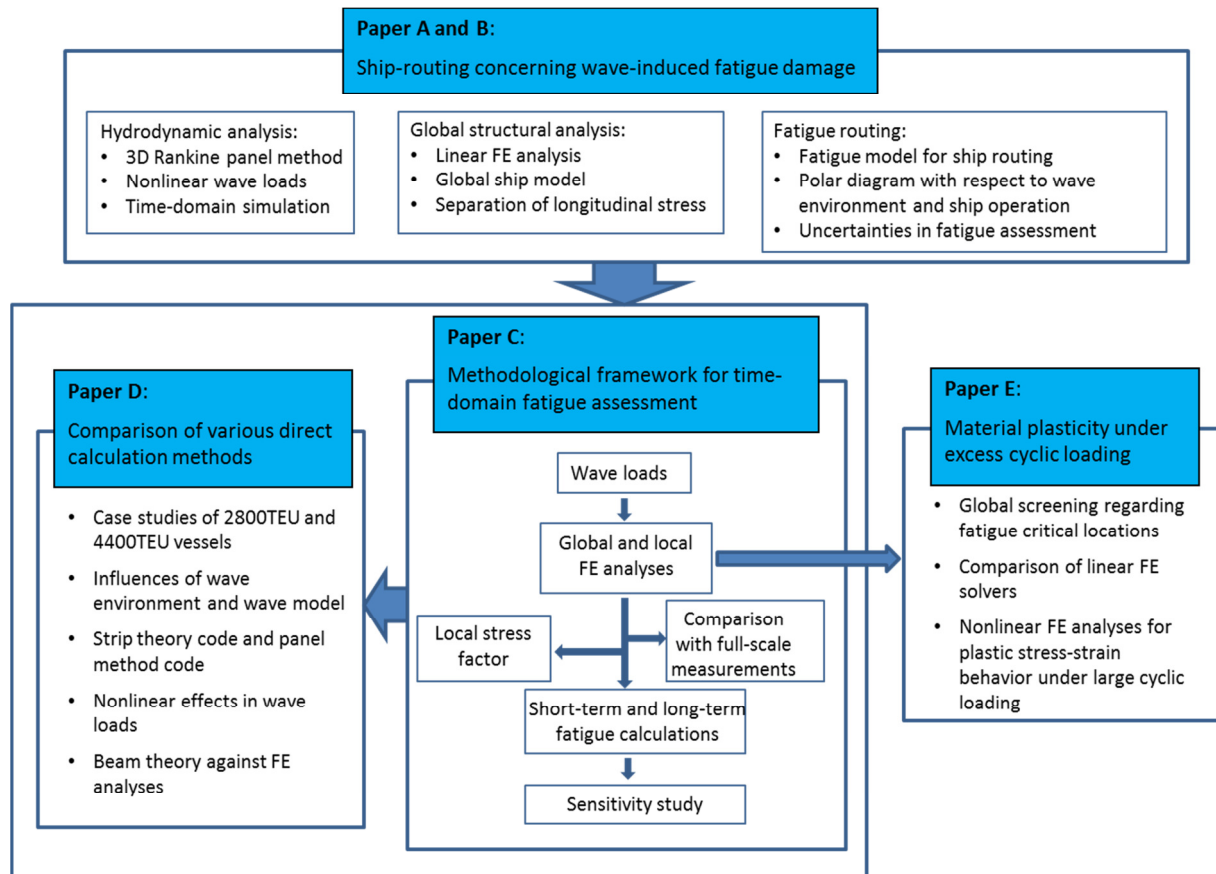


Fig. 2.1: Schematic overview of relationships between Papers A through E.

Paper A presents in-depth studies of wave-induced loads and the structural responses of an entire ship, which constitute the basis of a realistic modelling of wave-induced torsional loads on a container ship. Critical locations at the amidships and engine room bulkhead were selected for longitudinal stress analyses. Beam theory was utilised to separate the stress component from wave-induced torsion and illustrate the relationship between various stress components. Thus, fatigue damages due to various types of loading were quantified. It was also verified that fatigue damage accumulation varies significantly depending on the wave environment and the ship's operational features. For this reason, polar diagrams were plotted with respect to wave height, heading angle, and ship speed to be further developed as part of the fatigue routing tools.

Paper B presents an application of a ship-routing fatigue model with case studies of real-life container vessels. A simple fatigue model developed by Mao et al. (2010) was utilised to demonstrate the possibility and benefits of ship route planning leading to a reduction in fatigue damage accumulation. Case studies were performed using two container vessels operating in the North Atlantic trade. Model uncertainties involved in the ship-routing fatigue model were identified and investigated. Torsion-induced fatigue damage in container ships

and its relationship with the ship speed and the wave heading were discussed based on the findings in Paper A.

Paper C outlines a methodological framework for the time-domain fatigue assessment of ship structures. Local structural models were built and hotspot stresses were derived at side-shell longitudinals in connection to the transverse web under complex loading. Sensitivity and feasibility analyses of the proposed time-domain procedure were carried out, and fatigue life analyses were carried out by both the spectral method and the time-domain approach. In addition, a novel concept utilising a local stress factor (LSF) for deriving the stress concentration relationship between the global and local FE analyses was promoted and compared with traditional stress concentration factors (SCF).

Paper D compares the fatigue assessment results from different calculation methods. In addition to the proposed time-domain methodology presented in Paper C, four different commonly used direct calculation approaches were incorporated and compared in terms of wave description, seakeeping analysis, ship structural behaviour, fatigue stress derivation, and fatigue damage computation. The calculated results were also compared with full-scale measurements. This paper aims to address uncertainties involved in fatigue analysis procedure from a holistic perspective and is intended to serve as a useful reference in selecting various calculation procedures for ship fatigue assessments.

Paper E investigates the nonlinear material behaviour under cyclic loads. The local stresses at certain structural details of a case study vessel have been found to exceed the material's yield limit for a large number of cycles, thus questioning the pertinence of low-cycle fatigue in those cases. Thus, nonlinear FE analyses were carried out for side-shell structures under complex loading; it was found that the amount of accumulated equivalent plastic strains were generally small. The material response of repeated cyclic loadings was elastic shakedown, indicating that a linear FE analysis was sufficient for the investigated cases.

A series of procedures and numerical models are involved in the calculation procedure; for ease of reading, a brief summary of the application of these procedures and models in Papers A through E is presented in Table 2.1.

Table 2.1: Numerical models and approaches used in the appended papers.

		Paper A	Paper B	Paper C	Paper D	Paper E
Hydrodynamic analysis	Linear strip theory		X		X	
	Panel frequency-domain				X	X
	Linear panel time-domain			X	X	
	Nonlinear panel time-domain	X	X	X	X	X
Global structural analysis	Beam theory	X	X		X	
	Linear FE analysis	X	X	X	X	X
Local structural analysis	Sub-modelling			X		X
	Linear FE analysis			X	X	X
	Nonlinear FE analysis					X
Stress concentration	Tabulated SCF values	X	X	X	X	X
	SCF using the DNV method			X		
	LSF			X		
Stress or strain analysis	Nominal stress	X	X	X	X	X
	Hotspot stress	X	X	X	X	X
	Plastic strain					X
Short-term fatigue	Narrow band approximation		X		X	X
	Rain flow counting	X	X	X	X	X
Long-term fatigue	Spectral approach			X		X
	Time-domain approach			X		
Validation of numerical results	Full-scale measurement		X	X	X	
	Wave hindcast		X	X	X	
Case study vessels	2800TEU container ship		X		X	
	4400TEU container ship	X	X	X	X	X

3 Methodology

This chapter presents the methodology utilised in this thesis. It begins with a brief overview of general methodology for fatigue assessment and is followed by a description of the fatigue analyses routines recommended by major classification societies for ship structures. The methods used in this thesis are summarised.

3.1 Overview of the fatigue design methodology

Mechanical failures due to fatigue have been the subject of engineering efforts for over a century, but many problems still remain unsolved—not only for ship and offshore structures but for virtually all engineering structures. The complexity of the fatigue phenomenon is well known in the engineering community, and researchers have attempted to address the problem from a holistic perspective. Schütz (1996) crafted a comprehensive history of fatigue research, mentioning a number of distinguished scientists and engineers and their contributions to the development of fatigue knowledge. Similarly, Schijve (2003) surveyed the historical development of scientific and engineering knowledge concerning the fatigue of materials and structures in the 20th century, with the objective of presenting the current state of the art and aiming at calling attention to structural integrity. State-of-the-art reviews of fatigue life prediction methods for homogeneous materials, welded joints, and welded and non-welded structures were carried out by Dowling et al. (2009), Fatemi and Yang (1998), Cui (2002), and Fricke (2003).

Various methods for fatigue assessment currently exist and can be categorised differently. Fatigue assessment approaches are traditionally divided into stress-based (high-cycle fatigue), strain-based (low-cycle fatigue), and fracture mechanics approaches; see Dowling (2007). These major categories can be further divided depending on specific parameters, such as hotspot stresses, notch stresses, stress intensity factors, J-integrals, or other damage parameters, which fatigue life prediction is based on. The details of these approaches were comprehensively reviewed by Fricke (2003); however, Cui (2002) suggested that all existing fatigue assessment approaches can be generally grouped into two categories: cumulative fatigue damage theory and fatigue crack propagation theory. All methods except the fracture mechanics approach belong to the first category, where the fatigue damage cumulatively increases with the number of applied cycles. Another categorisation divides fatigue assessment methods into ‘global’ and ‘local’ approaches. According to Radaj et al. (2006), the global approach refers to fatigue assessments that proceed directly from the external forces of the moment or from the nominal stresses derived in the critical cross-section. A local approach refers to those methods involving local stress, local strain, or other local parameters. Within this categorisation, crack initiation, crack propagation, and final fracture are all defined as local approaches.

The stress-based approach, also known as the S-N method, is adopted by ship classification societies to calculate fatigue damage along with the Palmgren-Miner linear summation rule. In this thesis, the fatigue analyses are based on the S-N method. This approach implies that the reliability of fatigue analyses depends largely on the stress calculation. Fatigue assessments can be based on different definitions of stress—nominal, hotspot, and notch—that will be described in detail. Figure 3.1 illustrates the various types of stresses in a ship’s structure.

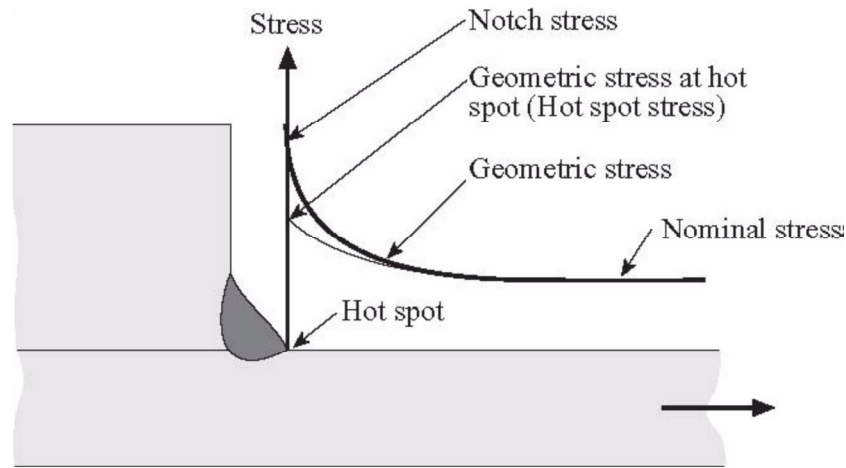


Fig. 3.1: Definition of different stress categories (DNV, 2010a).

Methods based on all these stress types are currently in use for the fatigue assessment of ship structures. The nominal stress approach is a traditional method for which extensive experience has been acquired over the years. However, due to the increasing demand for improved stress analysis accuracy, the nominal stress approach has been gradually replaced by the hotspot stress approach. Hotspot stress includes the increased stress due to structural discontinuities but excludes local stress concentrations due to the weld toe; it is extracted at a certain distance away from the weld toe. The hotspot stress method provides a fatigue assessment procedure for welded structures using available material behaviours obtained from welded and unwelded specimens; it is considered to be an effective engineering approach. Several variants of the standard hotspot concept have been proposed (Dong, 2001). Fricke and Kahl (2005) compared different hotspot stress approaches and concluded that fatigue life predictions based on different hotspot stress definitions were relatively similar; similar findings were presented by Kim et al. (2009). In this thesis, the ‘standard’ hotspot stress approach (as suggested in IIW (2008)) is used.

Fatigue damage can also be derived using notch stress methodology. A simple way to derive the notch stress is by incorporating an empirical SCF due to the existence of a weld bead. Another approach, the effective notch stress approach recently proposed by Radaj et al. (2006), assumes a fictitious notch radius that is based on ideal elastic material behaviour and micro-structural support effects. In comparison with methods using nominal stress and hotspot stress, the effective notch stress approach allows the effect of the local weld geometry to be directly included in the stress so that different geometrical configurations can be compared—and even be optimised—with each other. Furthermore, using the effective notch stress approach, it is possible to evaluate the weld root stress that cannot be derived from other approaches. The effective notch stress approach has received more attention with the rapid development of computational capacity; the IIW (2010) recently published a new fatigue assessment guideline for welded structures using this method. Several researchers (Fricke and Paetzold (2010), Garbatov et al. (2010), and Tran Nguyen et al. (2012)) have incorporated the effective notch stress approach in analyses of ship structural details. These efforts are expected to accelerate the use of the notch stress approach within the naval architect community.

3.2 Methods in the classification guidelines

Classification societies have published specific classification notes, recommended practices, or guidelines for how the fatigue assessment of structures should be performed. Two major approaches are commonly accepted: the ‘rule-based method’ and the ‘spectral method.’ Both methods are based on a long-term (typically 20-year) stress range distribution, and it is assumed that cyclic stresses occur as a consequence of wave loads—without considering the influence from hull girder vibrations. This section presents an overview of these methods; references are from the following classification documents if not particularly specified: the American Bureau of Shipping (ABS, 2004, 2011); Bureau Veritas (BV, 2008b); Nippon Kaiji Kyokai (ClassNK, 2003); Det Norske Veritas (DNV, 2010a); Germanischer Lloyd’s (GL, 2004, 2010); and the International Association of Classification Societies (IACS, 2008, 2009).

In the rule-based method, the long-term stress range is assumed to follow a certain type of distribution or spectrum. The stress components can be directly derived from general ship rules for global and local loads, which make this approach practical. Classification societies have suggested empirical formulas based on experience from existing vessels in which the wave loads and ship structural responses are considered implicitly. The stress range distribution depends on several issues, such as the ship type, ship length, location of the structural detail of interest, and operational environment.

Differences exist in the rule-based methods used by the different classification societies. The fatigue assessment is based on either the permissible stress range or the cumulative damage ratio. Various types of stress are in use in together with the corresponding S-N curves. Factors that can influence the fatigue resistance (mean stress, residual stress, and shakedown) are described in the guidelines of some classification societies but neglected in others. Thus, a fatigue life assessment using the rule load method varies significantly between classification societies (Fricke et al., 2002).

The spectral method is more sophisticated than the rule-based method. It is recommended by classification societies as a standard analysis procedure for vessels and structural details where fatigue resistance could be critical. This approach utilises numerical tools for the calculation of wave loads and structural responses. Because this approach considers the operation profile of a vessel (and because sources of uncertainties throughout the analysis are traceable and can be quantified), a fatigue analysis carried out using this approach provides more realistic results.

The spectral method assumes a linear relationship between the wave loads and stress response in ship structures. In other words, the fatigue loading acting on a vessel is considered as a linear problem. This approach assumes that the wave height is low compared to the ship’s length, resulting in minimised ship motions. Thus, the fatigue damage is thought to be primarily caused by small and moderate waves. Nonlinear effects, such as roll motions and the intermittent wetting of the side-shell in the splash zone, are either disregarded or approximated by correction factors.

3.3 The proposed time-domain method

In contrast to the two approaches recommended by classification societies, a practical time-domain procedure is proposed in this thesis. With this procedure, more sophisticated numerical tools can be utilised in the analyses of wave loads and localised stresses at hotspots, thus creating an improved fatigue damage calculation. Compared to the spectral method, this approach allows the nonlinear effects in wave loads and their influence on ship structural

responses to be calculated. The time-domain fatigue method is recommended in GL (2004) as an alternative approach but is not mentioned by other major classification societies.

3.3.1 Numerical tools and analysis procedure

Although the proposed time-domain procedure is particularly useful for container ships, the methodology can also be used for the analysis of other types of ships and offshore vessels. The calculation procedure is characterised by nonlinear time-domain hydrodynamic simulations followed by FE analyses. A numerical analysis procedure suitable for a time-domain-based direct calculation of fatigue damage in ship structures is illustrated in Fig. 3.2 and adopted from Paper C.

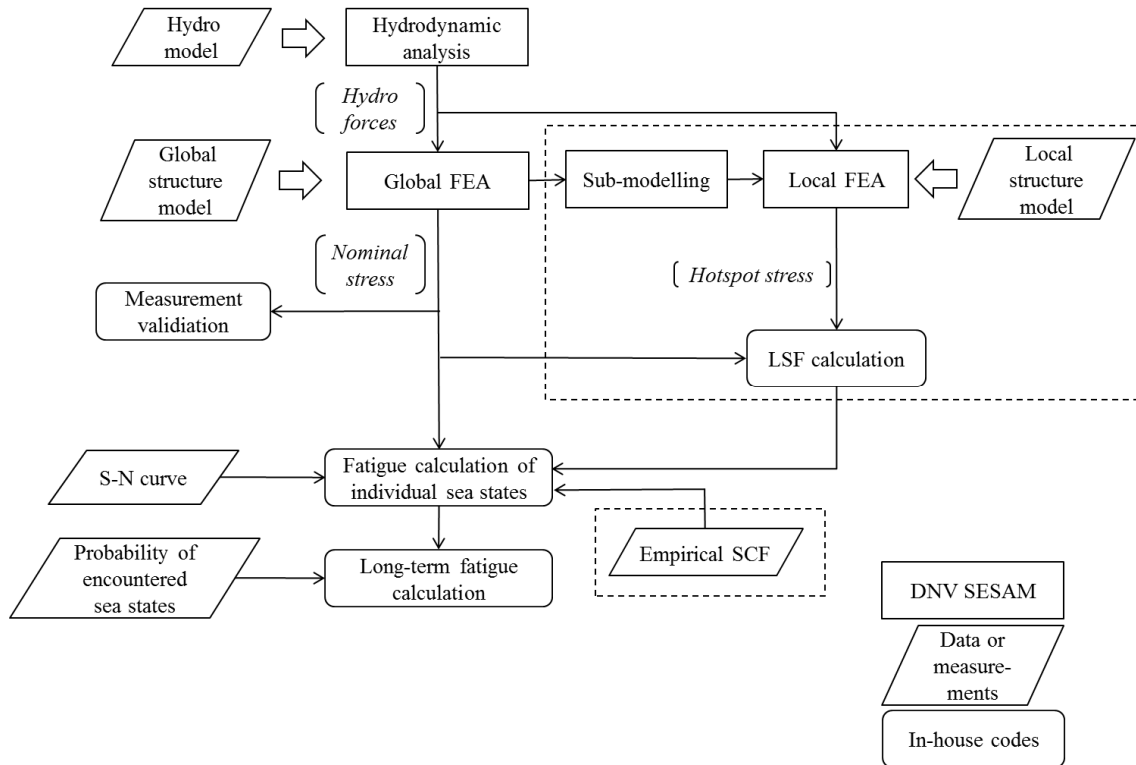


Fig. 3.2: Flowchart of analysis procedure for the direct calculation of fatigue damage.

In the flowchart shown in Fig. 3.2, a square-shaped symbol indicates that the DNV software SESAM (DNV, 2013b) has been used; a rhombus symbolises input to the analysis, such as material data/factors or results from prior analyses; a square with rounded corners denotes that an in-house code has been used in the calculations. The dashed areas indicate two options for the approximation or calculation of the local stress, either by a conventional SCF or by a developed LSF, as described in Section 5.2.2.

The DNV software SESAM is used for the hydrodynamic and structural analyses, whereas in-house codes are used for the stress evaluation and fatigue assessments. A time-domain hydrodynamic analysis is performed for each representative sea state, as illustrated in Fig. 3.3a. A global FE analysis is used for screening for fatigue-critical locations in the hull. Nominal stresses can be extracted from the global FE analysis in the locations of interest. By multiplying the nominal stress with a SCF, the hotspot stress can be calculated at the corresponding structural detail.

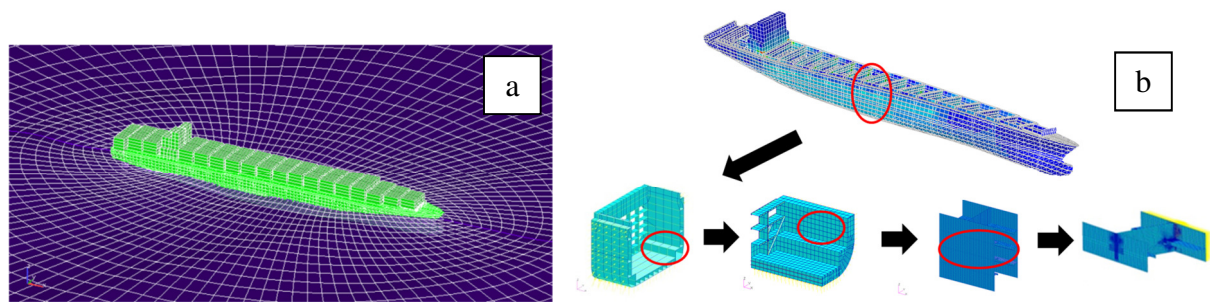


Fig. 3.3: Example of (a) hydrodynamic analysis and (b) various levels of FE models of the 4400TEU case study vessel.

A SCF can be determined through the tabulated values from classification societies or other references. Alternatively, the SCF can be obtained by a comparison of the hotspot stress from a local FE analysis with the nominal stress from a global FE analysis—according to class procedures. The latter approach is preferred for fatigue-critical locations where a SCF is unavailable or susceptible. In these locations, local FE models are created to investigate the local stress response in more detail. The hotspot stress can then be obtained from the local FE analysis through sub-modelling, which transfers the global loadings to the local FE model, as illustrated in Fig. 3.3b. Paper C provides a detailed description of the derivation of local hotspot stress.

3.3.2 Factors influencing fatigue strength

The fatigue strength is affected by many factors, including materials, surface roughness, shape and size, corrosion, and environmental temperature. The fatigue strength is essentially determined through tests of simple or component-like specimens or (in specific cases) the component itself. Fatigue strength is also influenced by the load spectrum and load sequence effects. Agerskov (2000) proved that the S-N data differ considerably between constant amplitude tests and those under different load spectra. Nevertheless, in the scope of this thesis, fatigue failure is assumed to occur when the accumulated damage is equal to unity (according to Palmgren-Miner's rule), regardless of variations in load spectrum and sequence.

For ship structures that feature welded joints, the same S-N curve is utilised, irrespective of such factors as weld profiling influencing the fatigue strength. However, surface weld discontinuity and misalignment are implicitly handled in the hotspot stress S-N curve, assuming good workmanship. Good coating and cathodic protections are also assumed, for which S-N curves in an air environment apply. This implies corrosion is ignored in general. Plate thickness effects are accounted for in the global fatigue screening and corrections are made for plates thicker than 25 mm according to DNV's recommendation (DNV, 2010a). Several issues considered particularly crucial for ship fatigue strength are addressed below.

Residual stress

Residual stress introduced by the welding process is an important factor in fatigue life prediction. Tensile residual stresses are assumed at welded joints in complex ship structure. When using the hotspot stress methodology, the tensile residual stress has been implicitly accounted for in the hotspot stress S-N curves. Fatigue tests on small specimens are performed under pulsating tensile loading (Lotsberg and Sigurdsson, 2006) to determine a hotspot stress S-N curve; the tensile residual stress may have been released before testing, or the residual stress may be in compression. The redistribution and relaxation of residual stress

are not considered in this thesis because the potential beneficial effects of early redistribution and relaxation under variable external loading are still under debate. This issue is reflected in common structural rules: the shakedown (here, residual stress redistribution) effect is accounted for in bulk carrier rules (IACS, 2009) but not in tanker rules (IACS, 2008).

Mean stress effects

Mean stress is another factor affecting fatigue life. Yoneya et al. (1993) performed a survey of second-generation VLCCs and found that fatigue life in side structures subjected to compressive mean stress was significantly longer than those subjected to tensile mean stress. The effect of mean stress was verified in the full-scale fatigue tests of side longitudinals reported by Lotsberg and Landet (2005). In this thesis, mean stress is treated differently, depending on the location of interest. In Paper A, regions in the base material not significantly affected by residual stress are under study, and the stress range in this case is reduced if the cyclic stress range is entirely or partially in compression. The mean stress reduction factor is calculated by following DNV (2010a). In other appended papers, it is assumed that the fatigue cracks always occur at the hotspots where tensile residual stress dominates. Thus, the mean stress effect is neglected at these locations.

Material properties

The fatigue strength of a component is associated with the strength of the material from which the component is made. However, for welded structures, fatigue cracking most often initiates at welded joints; increasing the strength of the parent material does not lead to an increase in the fatigue strength of the welded joints, as noted by Gurney et al. (2006). Thus, high-tensile steel is not specifically modelled in the fatigue analyses in Papers A-D even though various grades of steel are utilised in different parts of the investigated container vessels. The exception is Paper E, where hotspots in the base material were examined and the material properties were adopted by assuming steel with a yield strength of 277 MPa.

Stress multiaxiality

The commonly accepted S-N curves are generally based on test results from uniaxial loading, and hotspot stress S-N data are typically derived from a stress range normal to the weld toe. However, in real-life ship structural details, the hotspot stresses are more often biaxial, and the principal stress direction deviates from the normal weld. In these cases, using the maximum principal stress for fatigue assessment is considered conservative. Various recommendations deriving the hotspot stress for fatigue calculations exist. In IIW (2008), the hotspot stress is defined as the principal stress that acts approximately in line with the perpendicular of the weld toe, i.e., within $\pm 60^\circ$. If the principal stresses are outside of this range, the stress normal to the weld toe should be taken as the hotspot stress. DNV (2010a) recommends a similar approach as those prescribed in IIW (2008), but the maximum principal stress should be within $\pm 45^\circ$ to the weld normal. In this thesis, the fatigue hotspot stresses were derived following DNV's recommendation.

4 Case study vessels

In this thesis, two container ships, denoted 2800TEU and 4400TEU and shown in Fig. 4.1, are employed for case studies. Both vessels operate in the North Atlantic trade. The main characteristics of the vessels are listed in Table 4.1. They are selected for further study because full-scale measurement records are available for these two vessels; therefore, the numerical analyses can be verified by the measurement data. These two case study vessels are utilised differently in the appended papers, as summarised in Table 2.1.

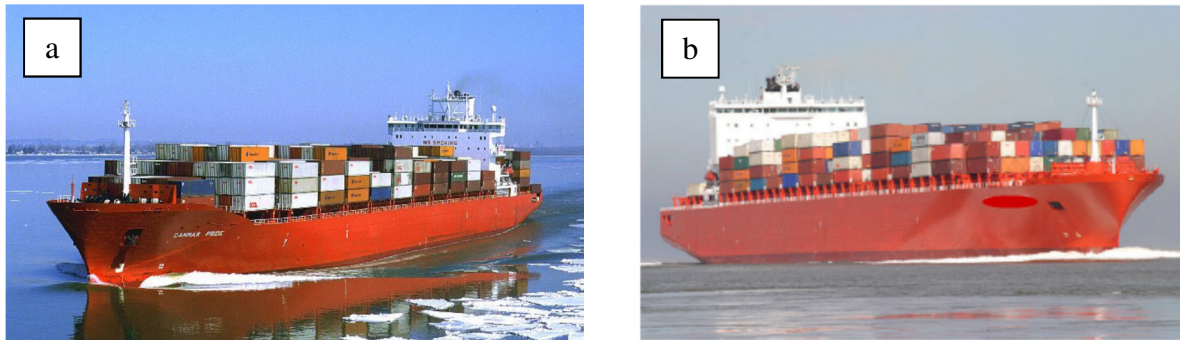


Fig. 4.1: Two container ships employed in the case studies: (a) the 2800TEU container ship; (b) the 4400TEU container ship.

Table 4.1: Main characteristics of two container ships used for the validation.

Max. TEU	2,800	4,400
LPP (m)	232	281
LOA (m)	245	294
Beam moulded (m)	32.2	32.2
Depth, moulded (m)	19.0	21.5
Design draught (m)	10.78	10.78
Block coefficient	0.69	0.69
Deadweight (tonnes)	40,900	47,754
Service speed (knots)	21.3	23.0
Vertical midship section modulus at deck (m ³)	39.16	32.19
Build year	1998	2003
Bow flare angle at 0.1 aft of FP	33°	35°
Bow flare angle at 0.05 aft of FP	40°	46°

Both vessels operate in the North Atlantic trade. The North Atlantic trade is considered one of the harshest sea environments in the world. During winter seasons, one to three low-pressure systems are expected for every crossing, and 15-25% of the significant wave heights encountered are greater than 5 m (Mao, 2010). For this reason, ship masters may choose alternative routes (rather than the shortest route) to avoid heavy weather. For the case study vessels, ship passages (including locations (longitude and latitude), ship speed, and sailing time) have been recorded along with other information. As an example, Fig. 4.2 presents the measured voyages of the 2800TEU container vessel during the first six months of 2008. It contains 14 voyages: seven voyages from Europe to North America and seven voyages in the opposite direction.

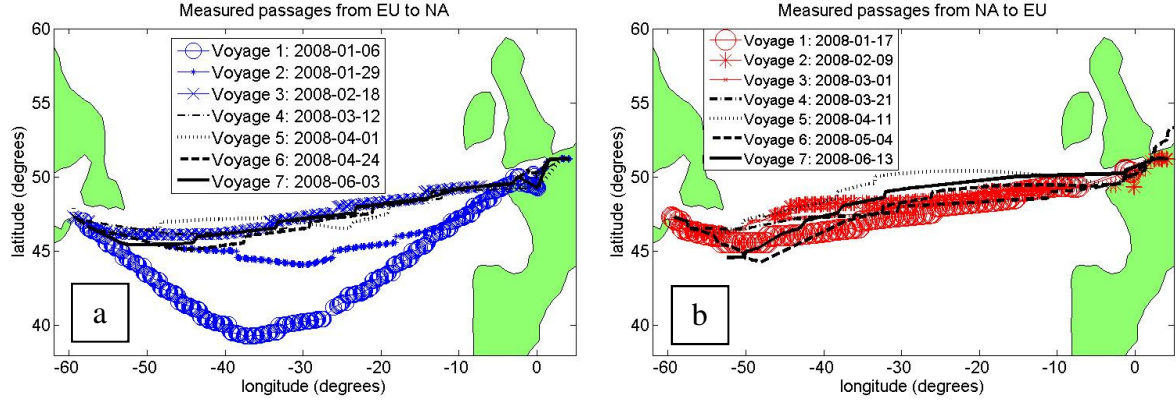


Fig. 4.2: Measured passages for the 2800TEU container ship during the first six months of 2008: **(a)** passages from Europe to North America; **(b)** passages from North America to Europe, where the departure time of each passage is indicated in the legend.

Both case study vessels are instrumented with standard hull monitoring systems following the DNV hull monitoring rules (DNV, 2005). The hull monitoring system is typically used on tankers and LNG vessels to provide onboard officers with information on the actual hull loading in terms of stress and bow acceleration, as well as wave and wind conditions. The devices of the hull monitoring system record real-time data of locations, ship motions, and wave, wind, and operational profiles, such as heading angle and ship speed. The hull monitoring system is comprised of strain gauges placed at various locations on the hull. Figure 4.3 provides examples of a wave radar and strain sensor. Throughout this thesis, the significant wave height H_s , the wave period T_p , and the mean wave direction were calibrated by using hindcast data from the ECMWF ERA-interim database (described in Section 5.1.2).



Fig. 4.3: Left: onboard wave radar (the navigation X-band radar) that measures the encountered waves. Right: deck longitudinal strain sensor at frame 179 on starboard side of the 2800TEU vessel. (Photos from Storhaug et al. (2007)).

There are four strain sensors in the 2800TEU container ship. The strain sensors are placed in the longitudinal deck stiffener on the port and starboard sides at frame 67 and frame 179, 50.3 and 118.7 m forward of the AP, respectively. The latter is slightly forward of midship section. The deck sensors are placed on the stiffener web (approximately 2 cm below the deck plate) and measure the nominal longitudinal strain without any significant global stress concentration factor. The sensor on the starboard side amidships is shown in Fig. 4.4. The manufacturing details for the strain sensors and the setup of the strain measuring system are further given in Storhaug et al. (2007).

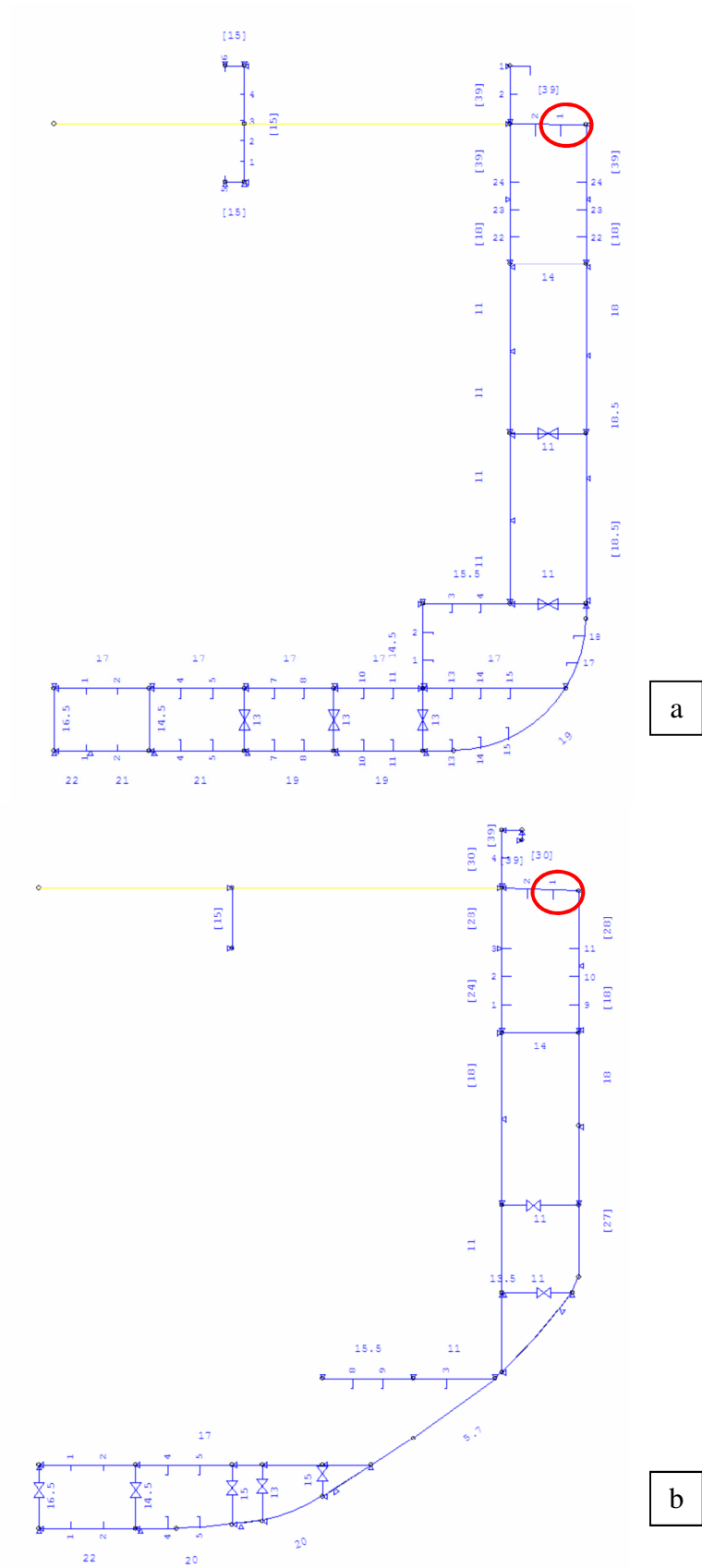


Fig. 4.4: Layout of the sensor locations in the 2800TEU container ship at two different cross-sections: **(a)** layout of midship cross-section with measurement position in upper deck; **(b)** layout of cross-section at aft section, close to the engine room bulkhead.

In the 4400TEU container ship, the sensors are only arranged in the midsection of the ship. They are located at the deck longitudinal (DL), side web (SW), side flange (SF), and inner side (IS), as illustrated in Fig. 4.5. The SF and SW sensors are placed in the outer side-shell to study the secondary bending stress effect due to sea pressure, whereas the IS sensors are placed in a position that provides almost the same warping stress as the DL position but with an opposite sign. Detailed descriptions of the strain sensors are referred to in Papers C and D, as well as in Storhaug and Moe (2007).

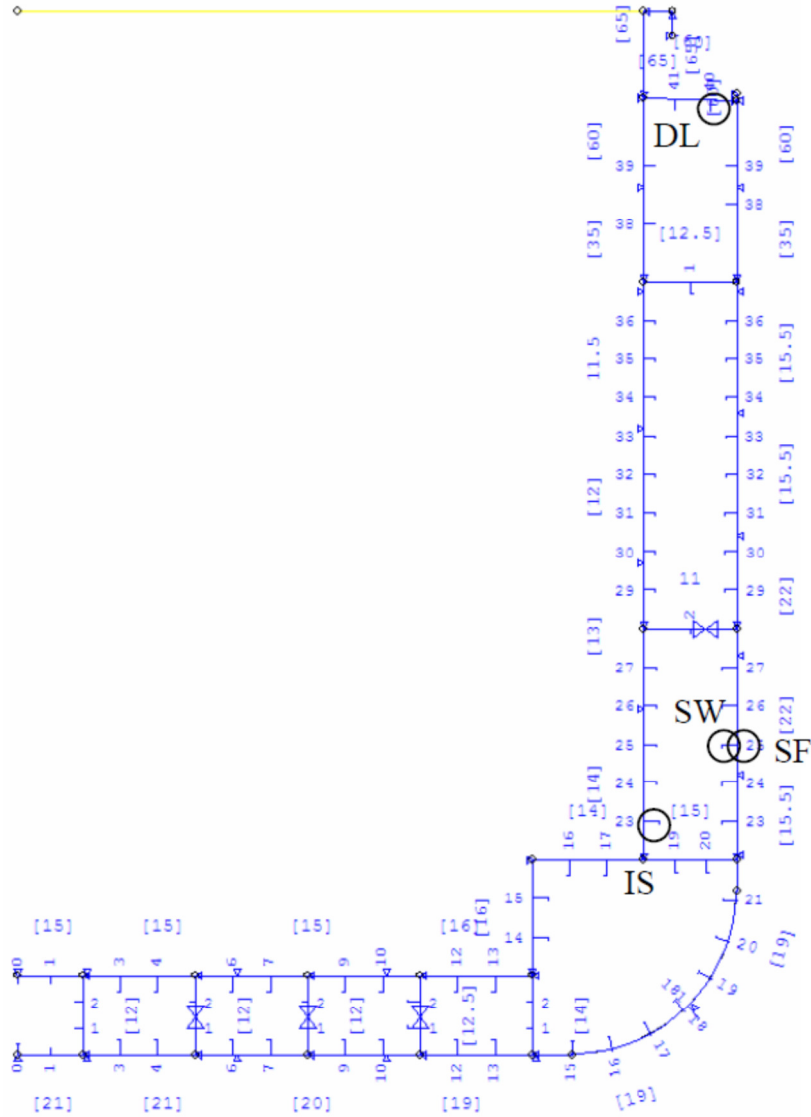


Fig. 4.5: The 4400TEU container ship, with strain sensors located on the deck and side-shell in the midsection (with measurement positions indicated).

5 Wave loads evaluation

Section 5.1 provides a brief description of the wave environment. The wave models employed in this thesis work are presented in Section 5.2. The wave loads on the ships are outlined in Section 5.3, beginning with an overview of the methodology, followed by discussions of essential issues of the nonlinear wave loads and ship motions; the wave loads on ship side-shell structures are then discussed.

5.1 Wave environment

The sea surface is irregular and changes constantly. An exact mathematical representation of the wave elevation as a function of such variables as time, wind speed, and wind direction is impossible. Therefore, the application of statistical methods is necessary to quantify wave characteristics. Wave elevation records can be treated as records of a random process. A stationary sea condition is typically defined by the significant wave height H_s (which denotes the average of the highest one third of the measured wave heights) and the wave period (such as the wave peak period T_p or zero-up-crossing period T_z).

5.1.1 Various measures of the encountered wave environment

The wave environments must be described with sufficient accuracy to correctly model the wave loads encountered by a ship. The sea environment can be measured either locally (through onboard wave measurement systems, such as wave radars) or through remote sensing techniques (such as satellite-borne sensors). In addition, wave environment estimations based on ship motions have become increasingly practical in recent years. Using this methodology, real-time directional wave spectra can be estimated based on measured ship responses. A review and application of this methodology is reported by Nielsen and Jensen (2011).

The probabilities of ship wave climates from different sources typically differ; consequently, considerable discrepancies are found in the resulting wave-induced fatigue damages. In this thesis, the distribution of H_s is compared among different sources: the measurement from the onboard wave radar of the 2800TEU container ship and a spatiotemporal wave model for H_s based on satellite measurements (Baxevasi et al., 2009) as well as those provided in the classification rules by DNV (2010c)—see Fig. 5.1, adopted in Paper D.

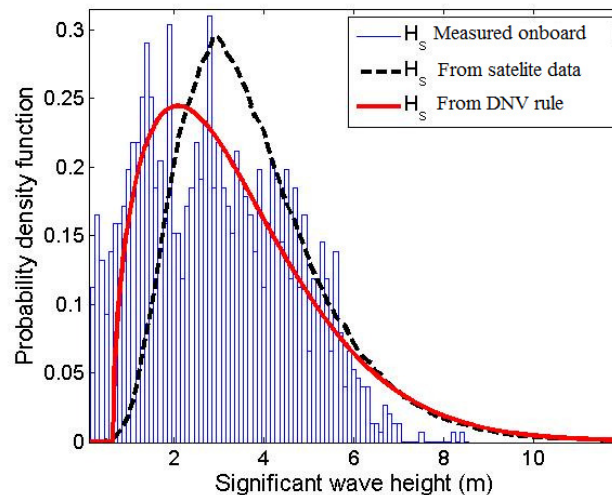


Fig. 5.1: Probability density functions of H_s from different sources. Scaled fatigue damage with respect to observed H_s ($D = 1.0$), DNV H_s ($D = 1.5$), and satellite H_s ($D = 1.6$).

As shown in Fig. 5.1, the onboard measured data include more moderate sea states ($H_s=1-5$ m) than the satellite model and DNV rule, whereas the probability of large H_s is almost identical between the DNV rule and satellite model (although higher than the observed data). The results also agree well with those reported by Olsen et al. (2006). If the fatigue damage caused by the onboard measured wave environments is assumed to be a unit, the damage computed using H_s from the DNV rule is 1.5, and the computed damage of the satellite model is 1.6. In this case, at least 50% of fatigue life prediction is due to the difference in H_s distribution. A detailed discussion is presented in Paper D.

5.1.2 Hindcast calibration of onboard wave measurement

Encountered sea states from onboard wave measurement systems are used as input for the wave loads in the current investigation. The measurements made from onboard wave sensing systems require compensation for the vessel motions and thus involve significant uncertainties. Although numerous attempts have been made to improve the ship-borne wave measurement instruments, a completely satisfactory onboard wave measurement system has not been achieved, and calibration of onboard measurement data is typically required. See recent reports on the reliability of onboard wave radar made by Mao et al. (2010), Fu et al. (2011), and Story et al. (2011).

Onboard wave measurements can be calibrated by numerical wave models, such as hindcast techniques, which have reached a reasonable state of maturity (Soares et al., 2002). The ERA-Interim is the latest global atmosphere reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). A detailed description of the accuracy, reanalysis model, and input observation can be found in Dee et al. (2011). In the scope of this thesis, hindcasted wave data are utilised in Papers B, C, and D.

5.1.3 Wave scatter diagram

The long-term variations of the wave environment can be described in terms of the distribution of governing sea state parameters (H_s and T_z) or scatter diagrams. A scatter diagram provides the occurrence frequency of a given parameter (e.g., H_s and T_z). The wave scatter diagrams cannot be derived from a theoretical method—they must be obtained from measurements. The most comprehensive measurements are the global wave statistics published by Hogben et al. (1986). This book contains tabulated values of H_s and T_z for 104 ocean areas (denoted Marsden areas) covering all major ship trading routes. The data are provided in increments of 1 m for H_s and 1 s for T_z for eight global directions. Jensen (2001) discussed the limitations and use of these data. Modifications on the average wave environments of four ocean areas in the North Atlantic (due to wave period inaccuracies) were made by Bitner-Gregersen et al. (1995); these modifications were endorsed by IACS Recommendation No. 34 (IACS, 2001).

The modified standard wave data for the North Atlantic contains a total of 306 sea states. In a typical fatigue analysis, eight wave headings are considered, resulting in total of 2,448 computation cases. This considerable number of cases implies intensive computation efforts for a time-domain analysis, thus making it infeasible. Thus, representative sea states are selected or designed based on a standard scatter diagram so that the total number of computation cases is kept to a manageable level. Various approaches for deriving a representative sea states exist; see Drummen et al. (2008), Jia (2008), and Storhaug et al. (2011). In the proposed time-domain fatigue procedure (as discussed in Paper C), a total of 20 representative sea states are selected, corresponding to significant wave heights of 1.5-7.5 m in the North Atlantic. See a detailed description of the representative sea states in Paper C.

5.2 Wave spectrum and spreading

In the fatigue assessment of ocean going ships, it is generally sufficient to assume a linear (Airy) wave model (DNV, 2010c). In general applications, the irregular waves in a sea state are assumed to be a Gaussian random process, which is uniquely defined by its spectrum and mean value. A wave spectrum describes the amount of wave energy at different wave frequencies. In practice, idealised wave spectra are used instead of the wave spectra derived at a particular time and place. The most common examples of these idealised wave spectra are the Pierson-Moskowitz (P-M) spectrum (that describes fully developed seas) and the Joint North Sea Wave Project (JONSWAP) spectrum (that describes developing seas). The JONSWAP spectrum is formulated as a modification of the P-M spectrum in a fetch limited situation. The details of both spectra are outlined in Paper D, among other literatures.

A wave is often considered “long-crested,” implying that all component waves propagate in the same direction. This is an idealised situation; in reality, sea waves are almost always spread in other directions and thereby characterised as “short-crested.” In the practice of ship design, the assumption of a long-crested sea may result in an overly conservative analysis of assumed head seas or following seas. However, directional wave components have a strong influence on a ship’s rolling motion and should not be overlooked as oblique waves. A short-crested sea can be modelled by including some spreading functions into the wave energy spectrum. In practice, the spreading function of a “cosine square” is often assumed.

The assumption of wave models, in particular the selection of wave spectrum and wave spreading, has led to variations in fatigue analysis results. In this thesis (as discussed in Paper D), four different wave models are used to generate the wave elevation. The first model is expressed by the P-M spectrum, both with and without energy spreading. The next model is described by the JONSWAP spectrum, with a peak enhancement factor of $\gamma=5$. The sea condition is assumed to continue for 30 min. A fatigue model developed by Mao et al. (2009) and the strip theory based code WAVESHIP (DNV, 1993) are employed for computation of the accumulative fatigue damages that are listed in Table 5.1. Because the ocean surface is generated from different wave models, the largest differentials of fatigue analysis can have a factor of 10 (for close-beam sea operations). It is well known that head sea operations are more crucial to ship fatigue design because more fatigue damage can accumulate in this situation. In this case, it has also been shown that different wave modelling will lead to fatigue damage variations greater than a factor of two. See Paper D for a detailed description.

Table 5.1: Thirty-minute accumulative fatigue damage (unit: 10^{-6}) of the 2800TEU container ship with various wave models for a sea state with $H_s=5$ m, $T_z=10$ s.

Wave spectrum models	U=10 m/s		U=5 m/s	
	Heading angle [°]		Heading angle [°]	
	180	80	180	80
P-M no spreading	47.1	0.4	25.2	0.4
P-M \cos^2 spreading	30.8	5.6	19.9	4.6
JONSWAP $\gamma=5$; no spreading	81.2	0.5	40.7	0.4
JONSWAP $\gamma=5$; \cos^2 spreading	49.0	7.8	30.9	6.4

5.3 Wave loads on ships

5.3.1 Overview of the methodology for wave load analysis

The evaluation of wave loads is essential for ship design. Various approaches exist that can be generally classed into the following categories: (1) the rule-based approach; (2) the experimental approach; and (3) the numerical approach.

The rule-based approach is a traditional methodology in ship design. The design rules specified by classifications societies are based on accumulated experience. The service data of existing vessels are summarised and interpreted with knowledge obtained from theoretical analyses and model tests in terms of formulae for future designs of similar ships. Although the rule approach is convenient, the limitations of this method are obvious; the rules are applied to general ship types without considering the structural and operational features of individual ships. It is unlikely that an optimal design for a specific ship can be achieved solely with rule formulations. Furthermore, in the absence of relevant previous experience, the use of design rules for new vessels implies that significant uncertainties may be introduced into the analysis results.

Tests with scaled models carried out in seakeeping laboratories have been used for many years to support the design of new ships and obtain data for the validation of theoretical and numerical seakeeping models. Before the advent of strip theory, model tests provided the only means for validating wave loads and ship motions in the design stage. Model tests have been traditionally used for seakeeping purposes, but model testing has also been utilised for specific studies, such as ship dynamics and fatigue analyses (see, e.g., Iijima et al. (2008), Senjanović et al. (2009) and Oka et al. (2011)). Model testing also enjoys the advantage of a controlled wave environment, which is lacking in full-scale trials. Modern ocean basin facilities are now capable of generating both regular and irregular waves in any preferred direction. However, some limitations of the model test still persist; the scaling problems can be difficult to overcome, and when motion control springs are utilised to maintain the course of a model ship in oblique waves, the ship's motions may deviate from reality due to the spring forces, resulting in significant uncertainties in the biased sectional forces.

Full-scale measurements are occasionally used to validate the results of numerical analyses and model tests for seakeeping and hull strength studies. When analyses, numerical tools, and model tests are unsatisfactory or involve too many uncertainties, full-scale measurements serve as the only means for achieving a reliable outcome. The existing literature illustrates that full-scale measurements on container vessels have attracted the attention of researchers around the world, and fatigue is one of the major concerns when full-scale measurements are performed (see Okada et al. (2006), Kahl and Menzel (2008) Heggelund et al. (2011) and Nielsen et al. (2011)). In general, these full-scale measurements are employed for two reasons: (i) to validate the design rules that are based on existing smaller vessels and (ii) to investigate the wave-induced vibrations particular to modern large container vessels.

With the advent of increased computational capacity, it is now more popular to compute wave loads with numerical methods. Computational fluid dynamics (CFD) provide the most realistic physical description in wave-ship interactions by directly solving Reynolds-averaged Navier-Stokes equations (RANSE). However, these simulations are prohibitively time consuming and not feasible when an entire ship hull must be considered (Kinoshita et al., 1999). For this reason, the CFD method is generally not applicable for wave load calculations in ship structural analysis.

In general, hydrodynamic loads in ship fatigue assessment applications can be computed through either strip theory or the panel method. Both approaches are based on potential flow theory. The assumption of an idealised fluid that is incompressible, irrotational, and inviscid greatly reduces the computational resources required by a fluid dynamics analysis, thus enabling the potential flow theory based codes commonly used in seakeeping applications. Earlier developments of numerical codes for wave loads and ship motions were based on strip theory. During the 1960s and 1970s, a variety of strip-theory-based codes were established, best represented by the STF method (Salvesen et al., 1970). In strip theory, the ship hull is treated as a series of strips that represent the cross-sections along the longitudinal direction. Many authors have reported that results obtained from strip theory generally agree with experiments in a vertical plane but are less satisfactory in a lateral plane (Beck et al., 2009). In recent decades, significant efforts have been devoted to nonlinear modifications of conventional strip theory (e.g., Jensen and Pedersen (1979), Fonseca and Guedes Soares (1998), Wu and Hermundstad (2002)).

The panel method was developed in the 1970-1980s; the hull form is modelled with reasonable accuracy by a number of panels. The wave loads are represented by water pressure loads distributed on these panels along the entire wet hull of the ship. In contrast to strip theory, the panel method considers full three-dimensional (3D) effects. According to Singh and Sen (2007), the panel method codes are broadly categorised into three groups: the frequency-domain Green-function method, time-domain Green-function method, and Rankine panel methods. The panel hydrodynamic codes are considered to provide better results with respect to ship motions and section loads in the lateral plane than strip theory codes.

5.3.2 Nonlinear wave loads and ship motions

Accurate representations of wave loads and ship motions are crucial for ship structural analysis. Along with the forward speed effect and 3D effects mentioned above, the nonlinear effects of wave loads and ship motions must be considered in a sophisticated hydrodynamic analysis. Wave loads on ships contain nonlinear terms—even if the wave itself is modelled as a sum of linear waves (higher order and nonlinear wave theories are outside the scope of this thesis). This nonlinearity originates from the hull geometry of the ship and is called geometric nonlinearity. The non-vertical hull form at the mean water line (both fore and aft) tends to promote more hull sagging moments than hogging moments. As a result, the bending moments and shear forces may increase in both amplitude and frequency, which should be accounted for in both ULS and FLS analyses.

The available hydrodynamic codes of practical design applications are developed with different levels of approximation. Cariou and Jancart (2003) carried out a comparative study of wave-induced loads on barge ship models from 22 levels of approximation. It was found that these various hydrodynamic codes provide significantly different results. They concluded that the geometric nonlinear effects should not be neglected in high sea states. This conclusion agrees with those of Watanabe and Guedes Soares (1999), who compared motion and load calculations for a realistic hull shape.

The current investigation uses the WASIM code, which is based on the 3D hydrodynamic Rankine panel method (DNV, 2006), and all calculations are performed in the time-domain. Waves can come from arbitrary directions and ship motions are calculated from all six degrees of freedom. Forward speed is included, and the incident waves can be modelled with various wave spectra and different spreadings. Details on the simulation setup are provided in Papers A, C, and D.

In WASIM, wave loads can be computed through either linear or nonlinear algorithms. For the linear solution, the Froude-Krylov and restoring hydrostatic forces are determined by integrating the pressure up to the mean wetted surface. The sea pressure above the mean wetted surface is always zero for the splash zone, whereas negative pressure exists below the mean wetted surface, leading to an unrealistic stress distribution in the splash zone if not corrected. In the nonlinear solution, the Froude-Krylov and restoring hydrostatic forces are integrated onto the instantaneously wetted hull. Thus, the nonlinear load caused by sea pressure near the mean free surface is modelled more realistically.

However, this nonlinear effect is still simplified because the radiation and diffraction parts are linearized and solved on the mean free and mean wetted surfaces. In fact, the nonlinear mechanism considered in WASIM represents only a certain degree of nonlinear phenomena. In this sense, WASIM must be categorized into the group of weakly nonlinear method. Nevertheless, the existing literature indicates that the nonlinearity accounted in WASIM is essential for solving nonlinear ship motions (ITTC, 2008), and it has been proven that nonlinear ship motions and hull girder loads computed from hydrodynamic codes similar to WASIM are in overall agreement with experimental results (Song et al., 2011).

Ships that operate in moderate- and large-amplitude waves are subjected to asymmetric vertical bending moment (VBM) due to hogging and sagging (Guedes Soares and Schellin, 1996). The ship's amidships response was examined to ensure that WASIM has the capacity to capture this asymmetry. By calculating the pressure according to the instantaneously wetted hull, the geometric nonlinearity due to the hull shape is also considered, yielding more accurate values for the wave-induced hogging and sagging moments. Nonlinear hydrodynamic analyses were carried out under four single regular waves with wave heights of $H_s=3, 5, 7$, and 10 m. An additional linear WASIM analysis was also performed at a wave height of 10 m (denoted as $H10lin$). All simulations were made in head sea conditions at a ship forward speed of 10 m/s (close to the service speed of 11.8 m/s). A positive value of VBM represents the hogging condition of the ship. The results presented in Fig. 5.2a illustrate that the nonlinear algorithm in WASIM captures the asymmetry of the VBM response amidships, in contrast to the linear analysis, which yields symmetrical results. Figure 5.2b illustrates that the asymmetry in the VBM response becomes more pronounced with increasing wave height.

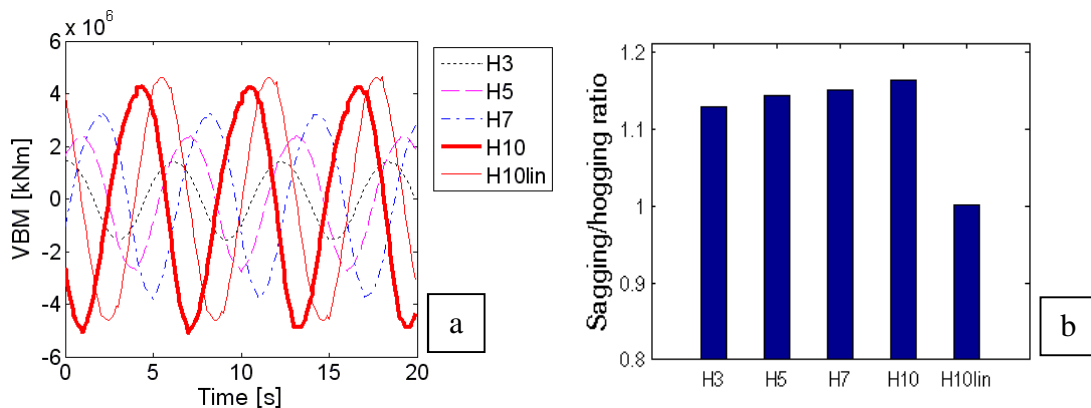


Fig. 5.2: (a) Illustration of the calculated vertical bending moment (VBM) and (b) ratio of sagging/hogging amidships under different wave heights; see the text for details.

5.3.3 Wave loads on side-shell structures

Wave loads applied to ship side-shell structures are complicated. In addition to wave-induced global loads, side-shell structures are also subjected to local pressure load and loads arising from the relative deflection of web frames or double hulls due to sea and internal loads. Although the global vertical bending stress is small for a side-shell (compared to deck and bottom structures), the horizontal bending stress is still significant. On the other hand, the amplitudes of the stresses caused by local loadings can be comparable to global stresses. Moreover, the local stresses close to the still water line tend to exhibit an increased number of cycles due to the intermittent wet and dry surfaces. Thus, the total stress in the side-shell can be significant in both amplitude and frequency, making the side-shell a fatigue-critical location.

Fatigue damage in ship side-shell structures has been frequently detected and repaired on ships. Although this problem was first reported in tankers (see Schulte-Strathaus and Bea (1991), ClassNK (1998), Yoneya et al. (1993), it has recently been reported in container vessels (see Müller (2003)). In the offshore industry, the same problem is to be expected for floating production storage and offloading (FPSO), where a large number of intersectional details of longitudinal and transverse structural members are of the same order as ship structures. The wave loads on side-shell structures must be treated with care in the design stage due to the consequences of repair and maintenance costs (in addition to the risk of oil leakage because of fatigue cracking in the side-shell).

Due to the relative motion between a ship and waves, the pressure load is particularly nonlinear with respect to wave height. This example of nonlinearity between wave height and pressure load cannot be accurately addressed through a traditional frequency-domain analysis. Researchers have attempted to account for this nonlinear pressure load using linear strip theory (see Friis Hansen and Winterstein (1995), Folsø (1998), and Berstad (1999)). These studies have succeeded (at various levels) in implementing linear strip theory to account for the sea pressure load. However, the wave loads and ship motions are derived from linear strip theory and are not as accurate as those calculated with the panel method. More detailed discussions are presented in Paper C, in which the proposed time-domain procedure is employed for the fatigue assessment of the ship side-shell longitudinals. Figure 5.3 illustrates the location and geometric configuration of the side-shell longitudinals on one side of a ship.

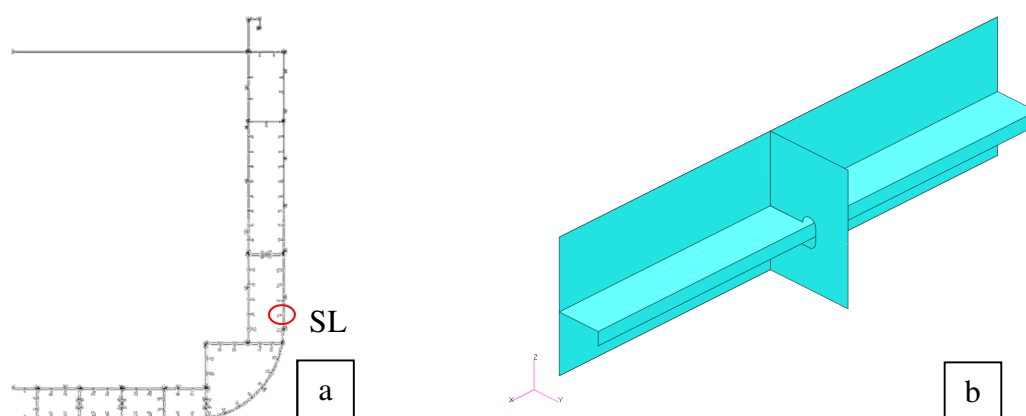


Fig. 5.3: (a) Location and (b) the geometric configuration of the side-shell longitudinal.

6 Structural analyses

This section describes the ship structural responses under wave loads to evaluate the resulting fatigue damage. Three major topics are covered: Section 6.1 summarises the derivation of the warping stress caused by the wave-induced torsional load. Its contribution to the total fatigue damage in relation to the stress components caused by horizontal and vertical bending is of interest (and discussed in detail in Paper A). Section 6.2 concerns the determination of local stresses for fatigue assessment that is discussed in depth in Paper C. Section 6.3 outlines the study of fatigue-critical locations with high local stresses using nonlinear FE analysis (addressed in detail in Paper E).

6.1 Warping stress in container ships

Global wave-induced loads are often divided into horizontal bending, vertical bending, and torsional loads. It is difficult to express warping stress due to wave-induced torsional loads in hull of a container ship with beam theory formulas. In contrast to the stresses caused by bending moments, the distribution of warping stresses is more complicated and strongly dependent on the geometrical configuration and longitudinal position of the cross-section along the ship's hull. Numerical tools such as the FE method and experiments are used to separate the stress components induced by different sectional forces. For example, Iijima et al. (2004) conducted FE analyses on entire ship models under design loads. An appropriate combination of stress components for the estimation of the total hull girder stress was proposed in terms of a quadratic expression, using coefficients to correlate the stress components. The combination of stress components was consistent with the full-scale measurement results reported by Okada et al. (2006).

Torsion-induced hull girder stress in container ships (and its contribution to fatigue damage) was investigated in depth this thesis. In Paper A, irregular wave loads were applied in the hydrodynamic analyses, with the resulting hull girder stress computed from FE analyses. The study was carried out on the 4400TEU case study container ship. Two cross-sections (where the maximum hull girder stresses were likely to occur) were studied: the cross-section amidships (AM) and the cross-section close to the engine room bulkhead (ER), as shown in Fig. 6.1. In each cross-section, the longitudinal stresses in the deck and the bilge (at locations i , ii , v , and vi) were investigated as assumed fatigue-critical locations. Finite element analyses indicated that the shear and normal stresses in the orthogonal direction at these locations were generally low compared to the longitudinal normal stresses and were thus ignored. See Paper A for further details.

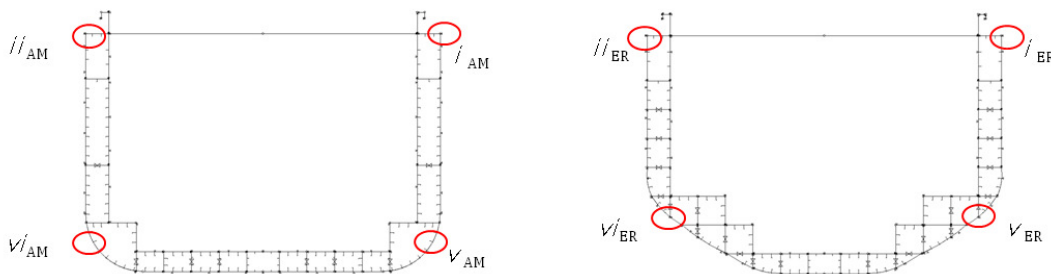


Fig. 6.1: The cross-sections under study. Left: amidships (AM); and Right: close to the engine room bulkhead (ER).

In this thesis, the longitudinal strength and fatigue characteristics of the container vessel are investigated by considering the longitudinal normal stress in the hull girder, σ_x . In a general

case for an arbitrarily loaded thin-walled open shell structure, beam theory suggests that the longitudinal stress σ_X can be comprised of four components: (a) a horizontal bending stress σ_{HB} , (b) a vertical bending stress σ_{VB} , (c) a warping stress σ_W , and (d) an axial stress σ_A . In this investigation, the axial stress component is assumed marginal and has been disregarded. Figure 6.2 presents the distributions of the other three stress components in an open transverse cross-section, which is typical for a container ship.

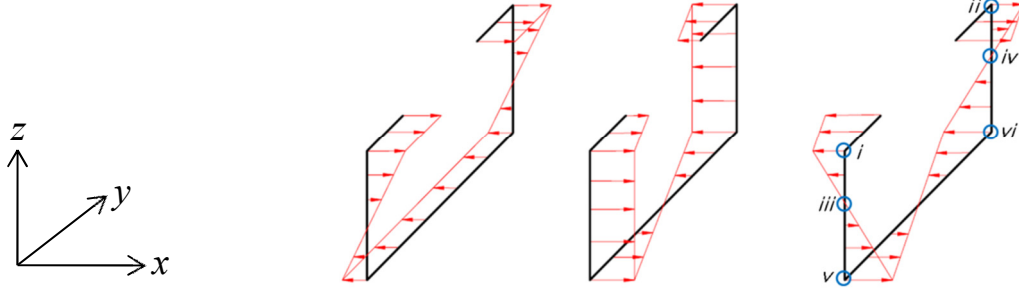


Fig. 6.2: Illustration of longitudinal stress distributions in a transverse cross-section of a container vessel; (to the left) vertical bending stress σ_{VB} , (in the middle) horizontal bending stress σ_{HB} , and (to the right) warping stress σ_W .

Assuming that elastic deformation conditions prevail, the longitudinal stress in each of the locations i to vi in Fig. 6.2 can be expressed by superposition as:

$$\sigma_X = \sigma_{VB} + \sigma_{HB} + \sigma_W + \sigma_A \quad (6.1)$$

In a symmetric cross-section, Eqs. (6.2) to (6.4) can define the relationships between stress components in the locations i to vi :

$$\sigma_{VB}^i = \sigma_{VB}^{ii}; \sigma_{HB}^i = -\sigma_{HB}^{ii}; \sigma_W^i = -\sigma_W^{ii} \quad (6.2)$$

$$\sigma_{VB}^{iii} = \sigma_{VB}^{iv}; \sigma_{HB}^{iii} = -\sigma_{HB}^{iv}; \sigma_W^{iii} = \sigma_W^{iv} = 0 \quad (6.3)$$

$$\sigma_{VB}^v = \sigma_{VB}^{vi}; \sigma_{HB}^v = -\sigma_{HB}^{vi}; \sigma_W^v = -\sigma_W^{vi} \quad (6.4)$$

If Eqs. (6.1) to (6.4) are combined, the following relationships for the longitudinal vertical bending stress, horizontal bending stress, and warping stress in location i can be expressed as

$$\sigma_{VB}^i = (\sigma^i + \sigma^{ii})/2 \quad (6.5)$$

$$\sigma_{HB}^i = (\sigma^{iii} - \sigma^{iv})/2 \quad (6.6)$$

$$\sigma_W^i = (\sigma^i - \sigma^{ii})/2 - (\sigma^{iii} - \sigma^{iv})/2 \quad (6.7)$$

By incorporating beam theory, the longitudinal normal stress σ_X was separated into various loading components. Taking cross-section AM as example: Fig. 6.3a presents the stress history of σ_X together with its stress components in the starboard deck, and Fig. 6.3b presents the stress history in the starboard bilge. The results indicate that σ_{VB} dominates in the deck, i.e., the other stress components are negligible. In the bilge, however, σ_{VB} is not the only

major stress component even though it still contributes the most to the total longitudinal stress σ_X . Non-conservative results can be obtained from a fatigue assessment if σ_{HB} and σ_W are neglected in this area. The results also illustrate that the stress components σ_{HB} and σ_W are coupled. In the bilge, these components are nearly in-phase and are therefore superposed onto the total stress. On the deck, however, these components are out-of-phase, leading to counteraction and, in some cases, near cancellation. See Paper A for a detailed discussion.

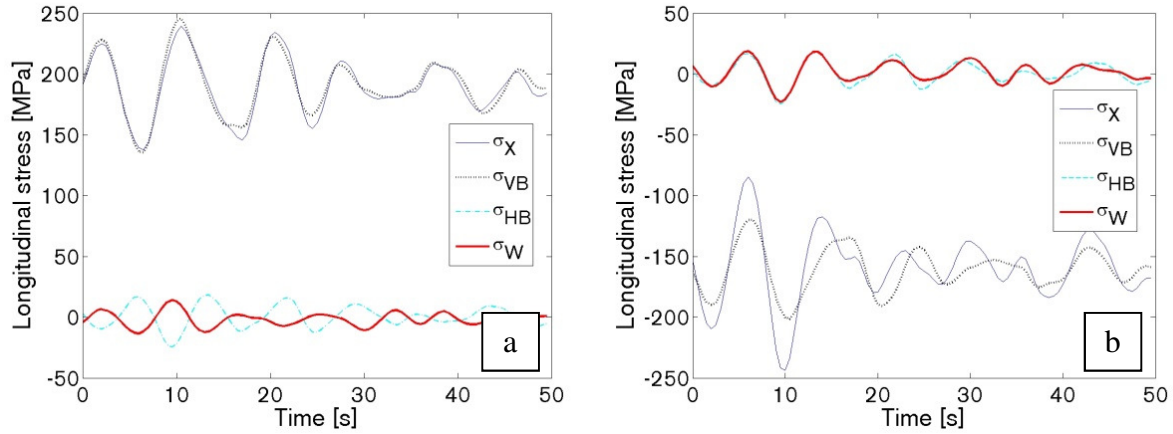


Fig. 6.3: Longitudinal normal stress and its components amidships: (a) in the starboard deck, and (b) in the starboard bilge.

6.2 Determination of the stress concentration

Even in a ship structure with good-quality welds (without major defects and details without misalignments), fatigue cracks can still occur in positions where local stresses are high. Local structural details in the deck, side-shell, and bottom are typical locations with high local stresses, and designing for persistence against metal fatigue is challenging. This problem is addressed in Paper C, which provides a detailed discussion on how to derive local stress for the purpose of fatigue assessment.

An accurate computation of hotspot stresses using a detailed FE analysis in all locations of interest in a ship's structure requires intensive computational resources and is not feasible in practice. Therefore, the nominal stress is multiplied with a SCF of specific detail to obtain the (local) hotspot stress instead. Consequently, the value of the SCF is critical for an accurate fatigue assessment because a small variation in the SCF leads to a large variation in the calculated fatigue life. Determining the SCF involves significant uncertainties. According to Sharp (1993), uncertainty in the value of the SCF accounts for 28% of the total uncertainty in a fatigue life calculation.

6.2.1 Tabulated SCF

Numerous design codes, handbooks, and other literature provide SCF in the form of graphs, look-up tables, and formulae for structures with typical geometric configurations, such as holes, notches, and shoulder fillets. The comprehensive book by Pilkey (1997) presented SCF for the most commonly used structural details. However, few of these structural details are ship-like details. Tabulated SCF values for ship-like details are provided by classification societies (see for example DNV (2010a)). These SCF are normally based on simplistic loading conditions, such as uniaxial loading and bending. The tabulated values are convenient to use in design practice, but any local stress derived from a tabulated SCF must be regarded as an approximation because of two aspects with respect to the discrepancy between the actual component and tabulated cases: first, the target geometrical configuration may differ

considerably from the tabulated one; second, loadings applied to an actual structural detail are typically more complicated in terms of type, amplitude, and phase. These discrepancies can result in stress concentration variations in real-life.

6.2.2 SCF derived from FE analyses

Stress concentration factors can also be derived by incorporating FE analyses. DNV (2010b) has proposed a procedure to obtain SCF in actual ship structural details. This procedure suggests two FE models with different levels of mesh resolutions, where the empirical loads are applied on both FE models. The nominal stress is estimated by the node stresses from a *semi-nominal-mesh* FE model with a typical element size of 50×50 mm, whereas the hotspot stress is extracted from a *fine-mesh* FE model, where the element size is $t \times t$, with t being the plate thickness of the structural detail. Figure 6.4 from Paper C presents an example of these two FE models for a portion of the outer side-shell structure of the case study container vessel. Various empirical loading types are involved, and the SCF is defined as the ratio between the summation of hotspot stresses and the summation of nominal stresses of all loading cases. Please refer to Paper C for a detailed description of this method.

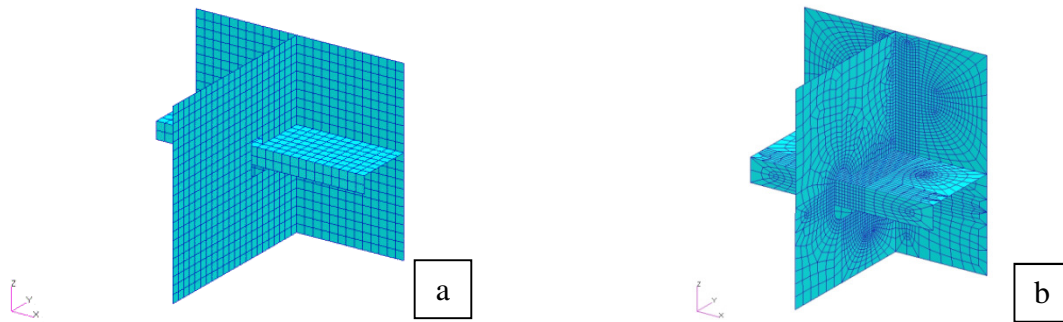


Fig. 6.4: FE models of a portion of the outer side-shell structure: **(a)** semi-nominal mesh (50×50 mm mesh) and **(b)** fine mesh ($t \times t$ mesh, where t is the plate thickness).

The geometrical configuration of the above FE models are invented by the author based on the scantling and may differ from the actual structural details. For instance, in actual ship structures, a longitudinal flange is often fitted with a web stiffener and even bracket on the top and/or with a lug at the side to prevent buckling of the longitudinal, but these supporting structural details are not considered in the current study. This structural design must be optimised and may help to partially explain the shorter fatigue life predicted in Section 7.3. Nevertheless, the purpose of using these FE models is to demonstrate the methodology for deriving local stresses for fatigue analysis without realistic intentions.

6.2.3 Derivation of the LSF for fatigue assessment

An approach for the derivation of local stress is proposed in Paper C. The idea behind this approach is that a stress concentration factor can be related to fatigue damages on the local and global levels and should be based on realistic loadings. The actual stress history should be used instead of simplified stress magnitudes from empirical or single load cases. An equivalent stress range is then defined to represent all of the stress cycles within a certain time period of the stress history (see Eq. (6.8)). In this case, $\Delta\sigma_{eq}$ is the equivalent stress range, m is a material constant (that is typically set at 3 for steel), $\Delta\sigma_k$ denotes the individual stress cycles identified by the rainflow counting (RFC) method, and N_k is the total number of stress cycles for the stress range k . The local stress is measured by the LSF, as defined in Eq. (6.9) (subscripts *hs*=hotspot and *nom*=nominal):

$$\Delta\sigma_{eq} = \left(\sum_k ((\Delta\sigma_k)^m / N_k) \right)^{1/m} \quad (6.8)$$

$$LSF = \Delta\sigma_{eq-hs} / \Delta\sigma_{eq-nom} \quad (6.9)$$

This approach is motivated by the fact that local stress responses are a result of a combination of all loads acting on the structure and their variations over time. Figure 6.5 (adopted from Paper C) presents an example of a longitudinal stiffener along the outer side-shell of the case study container vessel. The hotspot stress is extracted from (principal) stress records using the fine-mesh ($t \times t$) FE model. The nominal longitudinal normal stress is obtained from the full-ship global FE model, as illustrated in Fig. 3.3. In Fig. 6.5, the nominal global stress suggests that the stress is compressive because the side-shell structures are located below the neutral axis. However, the local response indicates that the principal stress is high and tensile. Therefore, a fatigue assessment must be carried out for these hotspots. See Paper C for a detailed description for implementing this procedure.

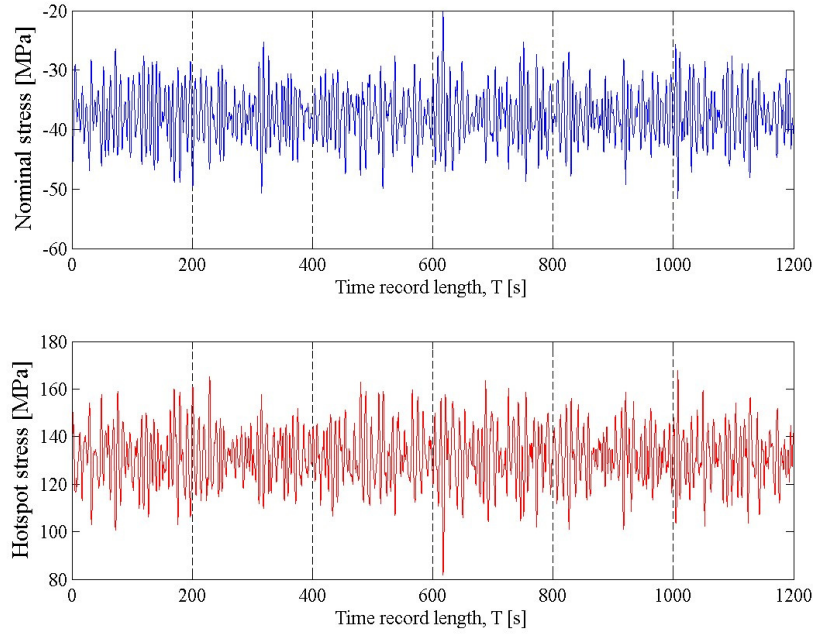


Fig. 6.5: Example of calculated stress histories in a longitudinal stiffener in the outer side-shell: nominal stress and hotspot stress for the LSF calculation.

The proposed LSF enjoys advantages in comparison with the tabulated SCF method and FE analysis method proposed in DNV (2010b). This approach relies on first-hand realistic and representative local stresses for true loading conditions that can be used in the fatigue life predictions. In addition, the LSF is based on fatigue damage analysis, which is closely related to the RFC technique, making the proposed methodology particularly useful for the time-domain procedure. Further discussion on the LSF approach is provided in Paper C.

6.3 Nonlinear FE analyses

In linear FE analyses, the local stresses in side-shell structural details occasionally exceed the yield stress of 277 MPa. An example from Paper E is presented in Fig. 6.6. Thus, the question arises of whether the S-N approach is violated and a strain-based fatigue approach is required.

In view of this inquiry, nonlinear FE analyses were performed to investigate the material response to cyclic loading during harsh sea states, which is presented in Paper E and summarised below.

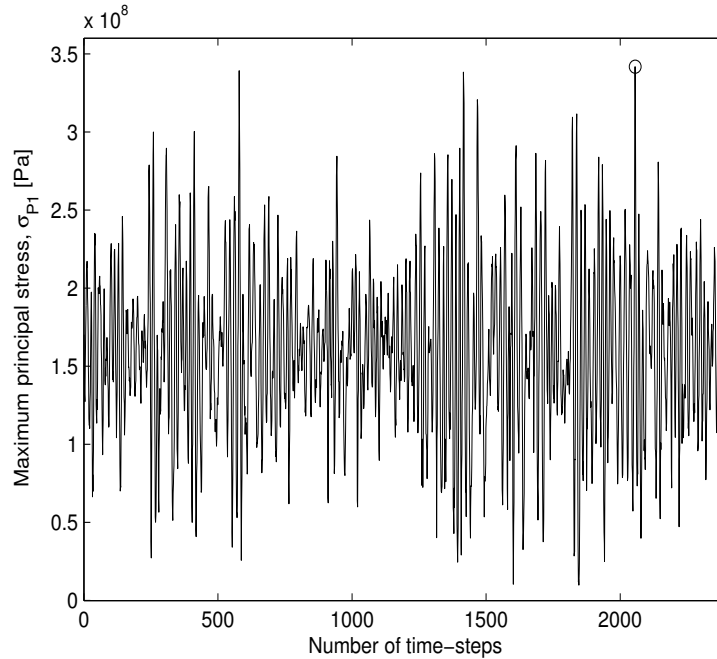


Fig. 6.6: Maximum principal stress in a hotspot from a linear FE analysis under significant wave height $H_s=7.5$ m. The circle indicates the peak maximum principal stress.

General structural analysis based on arbitrary loading and sea state conditions should not be limited to linear FE analysis. Therefore, Paper E presents the development of a methodology with an interface between SESTRA (DNV, 2008) and ABAQUS (ABAQUS, 2011) software programs that enables either linear or nonlinear structural analysis on global and local structure levels; the latter software enables nonlinear structure analysis. The methodology is used to numerically simulate and assess the structural response of the 4400TEU case study container vessel in a harsh sea state on the North Atlantic route during winter conditions.

The FE simulations of local details are first carried out in both SESTRA and ABAQUS for linear structural FE analyses—see Paper E for details. The results from these two solvers are almost identical, indicating that any errors due to the change of numerical code have been minimised. The same FE analysis cases (i.e., time-histories) were repeated using an ABAQUS solver with a nonlinear constitutive material model. The purpose was to study the magnitude of the accumulated equivalent plastic strain according to von Mises for the time histories.

The nonlinear structural FE analysis confirmed that the highest accumulation of equivalent plastic strain is located in the cut-out in the outer shell of the studied model. However, the plastic strain around this region is fairly low, and the rate of accumulation during cyclic loading decreased for every loading cycle. In additional FE analyses (those presented in Paper E), large wave loads representative of the highest local stress in Fig. 6.6 were applied. These analyses indicated that the stress-strain hysteresis curve resulted in elastic shakedown, i.e., a linear stress-strain relationship. The conclusion is that the current location of the local sub-model in the container vessel does not require a nonlinear FE analysis and strain-based fatigue assessment. Therefore, a stress-based approach can be used for the fatigue assessment for the studied local sub-model; see Paper E for the overall results of the nonlinear FE analyses.

7 Calculation of the fatigue damage

This section summarises the calculation of wave-induced fatigue damages and the use of computed fatigue damages in ship-routing tools. Short-term fatigue damage evaluations are discussed in Section 7.1, where the time-domain fatigue assessment procedure proposed in this thesis is summarised, in addition to the comparison of various approaches. Furthermore, fatigue caused by wave-induced torsion is discussed separately in Section 7.2. Section 7.3 describes the long-term fatigue calculation (or fatigue life prediction) using both the spectral and time-domain methods. The applications of mathematic models and damage polar diagrams as fatigue routing tools are outlined in Section 7.4.

7.1 Short-term fatigue damage calculation

The fatigue damage of ship structures can be calculated from either a time-domain or spectral approach. In cases when the stress history is available, the stress cycles (denoted S_i) can be extracted by various counting approaches, of which the RFC method is the most commonly accepted (Dowling, 2007). This approach identifies the local maxima that should be paired with the local minima to form a hysteresis loop, which is believed to provide best representation of the cyclic stress-strain behaviour of the material. The fatigue damage caused by the extracted stress cycles is calculated using the Palmgren-Miner cumulative rule, in combination with S-N curves, which are specific for various materials or structural details:

$$D = \sum_i \frac{N_i S_i^m}{\alpha} \quad (7.1)$$

In Eq. (7.1), N_i is the number of stress cycles at stress range S_i and m and α are the material parameters in the S-N curve.

Following a spectral analysis of hydrodynamic loads, the fatigue damage can be approximated in the frequency-domain by narrow band approximation (NBA), which assumes that the stress signals can be represented by a narrow band Gaussian process (Bendat et al., 1964). For the stress signal during period T , i.e. $t \in [0, T]$, the expected fatigue damage accumulated in one sea state for a linear S-N curve is approximated by NBA as:

$$E(D) = \frac{(2\sqrt{2\lambda_0})^m}{\alpha} T f_z \cdot \Gamma(1 + \frac{m}{2}) \quad (7.2)$$

where $\Gamma()$ is the gamma function, λ_0 is the variance of the stress signal within during period T , f_z is the zero up-crossing frequency, m and α are the material parameters in the S-N curve. It could be computed by the spectral moment of the stress if the process is described by its power spectrum.

7.1.1 Time-domain side-shell fatigue assessment

A numerical analysis procedure suitable for a time-domain based direct calculation of fatigue damage in ship structures has been presented in Fig. 3.2. The numerical analysis procedure is demonstrated by using side-shell fatigue assessment of the 4400TEU ship in Paper C. The calculation procedure is characterised by nonlinear time-domain hydrodynamic simulations followed by FE analyses. The nonlinear wave loads applied on the side-shell structures have been previously mentioned in Section 5.3.3, and the derivation of local stress and proposed LSF has been discussed in Section 6.2. In this sub-section, several essential issues of fatigue damage calculation are highlighted and summarised.

The time record length and timestep interval influence the fatigue damage results. Timesteps of 0.1 s for hydrodynamic simulations and 0.5 s in FE analyses are used to obtain a balance between engineering accuracy and computational effort. For short-term fatigue damage estimations, a time history of 20 min is typically sufficient for a single realisation, although more realisations are necessary for investigating the uncertainties associated with numerical analysis. See Paper C for a detailed discussion.

Both linear and nonlinear wave load algorithms of WASIM are used to calculate the global wave loads applied on the side-shell structures. The results indicate that there is some variation between the linear and nonlinear simulations; however, the difference is relatively small. Nevertheless, linear WASIM only integrates pressure up to the still water line and should thus be considered as an approximation of the nonlinear solution. In these global FE analyses, the calculated girder stresses appear to be dominated by global girder forces. The sea pressure load applied on the side longitudinals must be further assessed through local models. Overall results and further discussions are provided to in Paper C.

7.1.2 Comparison of various methods

Numerical codes are widely employed today in the practice of ship structural analysis, including fatigue assessment. These codes are based on various theories with different levels of complexities. However, there is no consistent evidence that one approach is more accurate than the others in all cases. The use of different methods for the same vessel typically yields various results in calculated fatigue damage. Thus, a comparison is needed to rationally investigate the reliability of common direct calculations. The objective is to contribute to a better understanding of direct calculation methodology in the application of fatigue assessment of ship structures. In Paper D, the short-term fatigue damages of the 4400TEU vessel are calculated using five direct calculation methods (referred to as Approaches 1 through 5) and summarised as follows:

- *Approach 1 (Strip)*: Ship motions and sectional loads are calculated using WAVESHIP. The fatigue stresses at the deck level are represented by the vertical bending moment divided by the vertical sectional modulus. The fatigue damage is calculated using a NBA in this approach.
- The fatigue stresses at the deck level are represented by the vertical bending moment divided by the vertical sectional modulus. The fatigue damage is calculated using a NBA in this approach.
- *Approach 2 (Panel FD)*: The hydrodynamic loads and ship responses are calculated using the frequency-domain WASIM. The stress ranges are derived from the vertical bending moment divided by the vertical section modulus, and the fatigue damage is approximated from the NBA.
- *Approach 3 (Panel linear)*: The wave loads and ship motions are calculated in a time-domain WASIM. The stress records are obtained from the vertical bending moment history divided by the vertical sectional modulus. The rainflow analysis is carried out by WAFO (WAFO-group, 2000).
- *Approach 4 (Panel nonlinear)*: The same as *Approach 3*, except the nonlinearity is considered in the hydrodynamic analysis.

Approach 5 (Panel FEA): The hydrodynamic simulations are the same as in *Approach 4*. The hydrodynamic loads are transferred to the FE model with a time interval of 0.5 s. The

fatigue stress is computed by a FE analysis, and the fatigue damage is determined from the RFC method.

Table 7.1: Major characteristics of the various approaches.

Approach	Wave loads	Stress calculation	Fatigue calculation
1	Strip	Beam theory	NBA
2	Panel FD	Beam theory	NBA
3	Panel linear	Beam theory	RFC
4	Panel nonlinear	Beam theory	RFC
5	Panel nonlinear	FEA	RFC

In Paper D, the fatigue damages on the deck level in the midship cross-section were investigated, and all measurements and numerical analyses were carried out for these locations. One of the strain sensors (the deck longitudinal (DL)) on one side of the 4400TEU vessel is shown schematically in Fig. 4.3. Similarly, the strain sensors are also located on the opposite side. The fatigue damages are obtained using information from strain sensors at locations in the starboard and port sides, respectively, denoted as DLS and DLP. The term DL is used for *Approaches 1-4* because the fatigue damages at the starboard and port sides are identical.

Three actual sea states from a winter voyage of the 4400TEU case study vessel are selected for comparison, representing high-, median-, and low-wave environments, respectively. The numerical simulations and measurements for short-term fatigue analyses in Papers C and D are based on these sea states and the operational profiles listed in Table 7.2. The hotspot stress S-N curve DNVC-I is applied and an empirical SCF of two is assumed, following the recommendation of Storhaug and Moe (2007). This S-N curve and the assumed SCF are applied for all fatigue calculations of the 4400TEU throughout this thesis unless specified otherwise.

Table 7.2: Primary data of the studied sea states.

Sea state	Date and time	H_s [m]	T_p [s]	U [m/s]	Heading [°]
1	20081217, 08:00-09:00	6.1	13.7	8.5	130
2	20081217, 17:00-18:00	4.7	12	9.7	140
3	20081216, 21:00-22:00	3.5	10	10.2	160

The calculated mean fatigue damages, as well as the standard deviations from different approaches, are presented in Table 7.3. In general, all of the approaches provide reasonable fatigue damages under the studied sea states. For the stress evaluation using beam theory, vertical bending is the only sectional force that has been considered. In other words, horizontal bending, torsional, and shear forces are not involved in the fatigue assessment, which indicates that vertical bending moment dominates the longitudinal stress on deck, at least for container ships. A detailed description of the measurement and simulation setup, as well as the overall results, is provided in Paper D.

Table 7.3: Twenty-minute accumulated fatigue damages of measured and calculated data. (DLS: deck longitudinal starboard; DLP: deck longitudinal portside; std: standard deviation).

Accumulated fatigue damage (1×10^{-6}) during 20 minutes										
Sea state	Measured				Strip (Appr. 1)	Panel FD (Appr. 2)	Panel linear (Appr. 3)	Panel nonlinear (Appr. 4)	Panel FEA (Appr. 5)	
	DLS		DLP		DL	DL	DL	DL	DLS	DLP
	mean	std	Mean	Std						
1	72.5	5.83	80.5	4.76	110.6	68.3	85.2	110	69.3	95.8
2	29.8	4.04	43.0	4.43	63.8	50.4	29.1	33.0	34.8	54.3
3	15.9	1.62	18.7	1.47	16.9	19.7	19.4	19.1	18.2	26.3

Table 7.3 indicates that fatigue damages from the FEA approach—in all sea states—exhibit general agreement with the results from the measurements. The FEA approach provides better fatigue estimation on the windward side (starboard in this thesis) than on the leeward side, perhaps because the hydrodynamic code overestimates wave loads on the leeward side. Further investigation about the variation in fatigue damages between the windward and leeward sides seems desirable. Furthermore, the fatigue damages calculated from ‘Panel linear’ differ than those from ‘Panel nonlinear,’ and the difference increases with increasing wave height, although the difference is generally small for the investigated vessel. The comparison between the ‘Panel linear’ and the ‘Panel FD’ approaches indicates a NBA gives similar fatigue estimation as RFC for the wave frequency loads. The results also indicate that the strip method provides agreeable fatigue estimation under relatively small waves. However, when the wave height increases, fatigue damages from the strip theory code become less satisfactory. A detailed discussion is provided in Paper D.

7.2 Fatigue damage due to wave-induced torsional loads

Fatigue damage due to wave-induced warping stress in container ships has been investigated in Paper A and is summarised in this sub-section. The fatigue damage calculation is based on the separated stress components, as described in Section 6.1. Fatigue damages are computed in the midship and engine room bulkhead cross-sections at the locations illustrated in Fig. 6.1. The global nominal stresses extracted from the global FE model are used for fatigue damage calculation. When considering the total longitudinal stresses in the bilge area of container vessels in Paper A as being compressive, a reduction factor of 0.6 in the calculation is multiplied with the nominal stress range according to DNV (2010a).

Five heading angles are analysed to investigate the wave-load-structure interaction for different wave encounter directions. The same incoming wave, with a significant wave height of $H_s=5$ m and a wave period of $T_z=12.4$ s, was used in all headings. The accumulated fatigue damage for each heading angle was based on a stress history of the total longitudinal stress under a 20 min stationary sea state at a ship speed of 10 m/s. More details on the setup of numerical simulations and overall results are presented in Paper A. Figure 7.1 presents the fatigue damages on the deck and in the bilge and how they were affected by the heading angle for the midship cross-section. The calculated fatigue damages in these locations were also compared with the accumulated fatigue damage based only on the vertical bending normal stress σ_{VB} , i.e., where the horizontal bending and warping stress contributions were disregarded. Similarly, the results for the cross-section in front of the engine room are presented in Fig. 7.2.

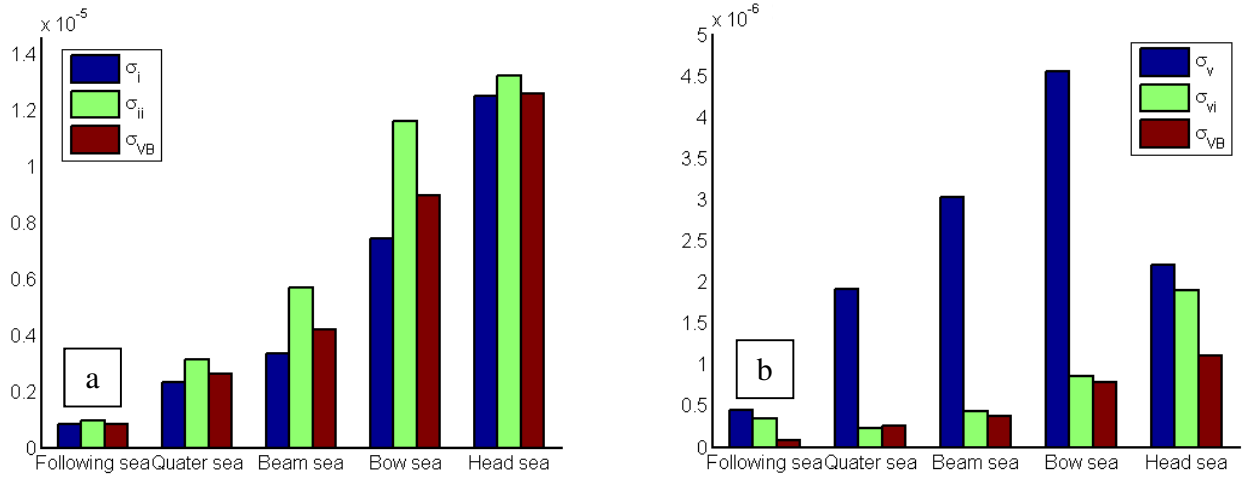


Fig. 7.1: Influence of heading angle on the accumulated fatigue damage in the amidships cross-section: (a) on the deck and (b) in the bilge. The accumulated fatigue damage is calculated using a 20 min stress history for stationary sea state conditions.

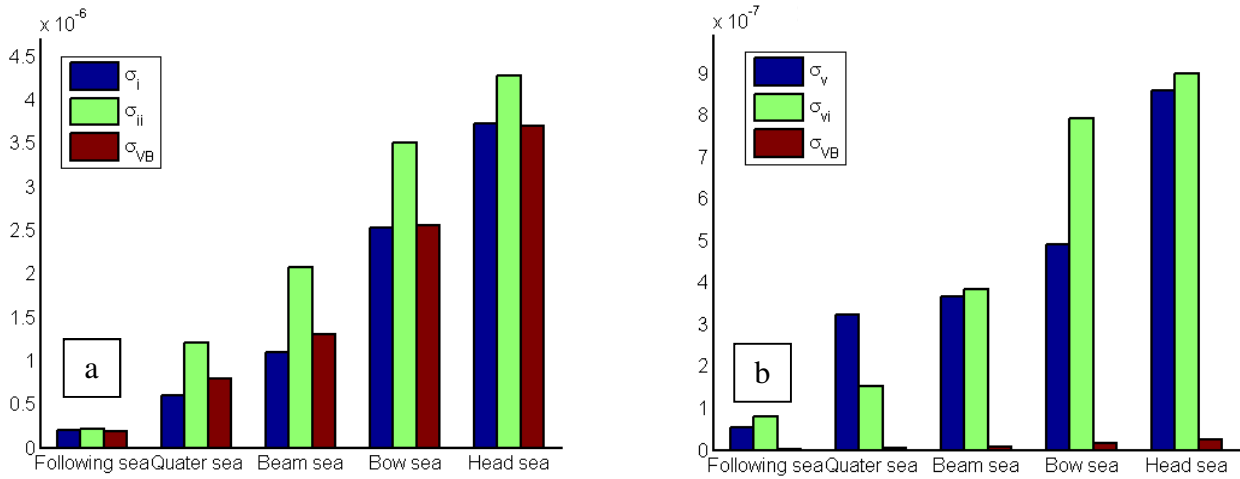


Fig. 7.2: Influence of heading angle on the accumulated fatigue damage in the cross-section ahead of the engine room: (a) on the deck and (b) in the bilge. The fatigue damage is calculated using a 20 min stress history for stationary sea state conditions.

Fatigue damages caused by horizontal bending and torsion are found to be slight on the deck but substantial in the bilge area. Figures 7.1 and 7.2 illustrate that the accumulation of fatigue damage increased if the heading angle approached head seas, thus encountering more waves. This is particularly true for fatigue damages on the deck. This result can be explained by the predominant stress component σ_{VB} on the deck. However, performing a fatigue analysis based only on σ_{VB} is not recommended because fatigue damages on the port and starboard sides can differ, and the stress component σ_{HB+W} causes at least one of these components to exceed the fatigue damage caused by σ_{VB} . This feature is more obvious in oblique waves. In contrast, the accumulation of fatigue damage in the bilge area is significantly affected by the stress component σ_{HB+W} , causing the largest accumulation of fatigue damage to occur during bow sea conditions. Furthermore, the difference in fatigue damages between the port and starboard sides becomes greater compared to those on the deck due to the more dominant σ_{HB+W} . Thus, only considering σ_{VB} in the fatigue assessment of the bilge area is not conservative.

7.3 Long-term fatigue damage estimation

A long-term fatigue assessment can be carried out by using the spectral method in the frequency-domain or the time-domain method. The former method requires significantly less computational effort than the latter. Therefore, the spectral method is often used for long-term fatigue assessments and for global fatigue screening of the entire ship's hull to identify the fatigue-critical locations. However, the time-domain method is preferred for structural details where wave loads exhibit nonlinearities, e.g., side-shell structures. Therefore, both the spectral method and time-domain method are investigated here. Linear and nonlinear WASIM solvers are used in hydrodynamic simulations for the spectral method and time-domain method, respectively; see Paper C for details.

7.3.1 Fatigue life prediction using the spectral approach

In the spectral method, the ship response is assumed to be proportional to the wave height, which can be described as a superposition of the responses of all regular wave components that comprise an irregular sea. The long-term distribution of wave loads may be estimated from wave statistics, where the scatter diagram is assumed to be equal for all wave directions. Based on the assumption of linearity, the ship response spectrum can be derived directly from the wave spectrum by using unit wave heights.

The short-term stress range can be assumed to be Rayleigh distributed within each short-term condition. The stress range distribution for a given sea state i and heading direction j can be expressed by Eq. (7.3), where m_0 is the zero-order spectral moment:

$$F_{\Delta\sigma ij}(\sigma) = 1 - \exp\left(-\frac{\sigma^2}{8m_{0ij}}\right) \quad (7.3)$$

The long-term fatigue calculation is based directly on a scatter diagram and utilises the response spectrum and S-N curves as input. The total fatigue damage during the service life is a sum of all sea states over all wave directions, considering the weighted relative probabilities. Alternatively, the long-term fatigue damage can be estimated from the long-term stress range distribution that is assumed to follow a Weibull distribution, according to Eq. (7.4), where h is the shape parameter and q is the scale parameter. These parameters are the average values of the entire stress range distribution calculated by fitting the Weibull function to all distribution points through a least-squares technique.

$$F_{\Delta\sigma}(\sigma) = 1 - \exp\left(-\left(\frac{\sigma}{q}\right)^h\right) \quad (7.4)$$

The global FE model (as illustrated in Fig. 3.3) is used for global fatigue screening to identify the fatigue-critical locations. A full stochastic fatigue assessment is performed in the frequency-domain assuming a wave environment of the North Atlantic (IACS, 2001). The target service life of the case study vessel is 20 years, with 85% time at sea. The commercial code STOFAT (DNV, 2009b) is employed, and the fatigue damage is calculated based on the nominal stress derived from global FE analyses. The spectral method used in Papers C and E excludes the splash zone pressure correction, which leads to uncertainties for results in areas close to the splash zone. See Papers C and E for a detailed description of the setup of the numerical simulations.

Figure 7.3 presents an example of the global fatigue screening results in terms of the usage factor. The usage factor is defined as the design life divided by the calculated fatigue life. For example, if the usage factor is 1.0, it will result in fatigue failure after 20 years. Figure 7.3 indicates that the usage factor in the most critical region is relatively high, with a usage factor of 3.8, which corresponds to a calculated fatigue life of five years. This calculated fatigue life is too low to be realistic. However, values from a global fatigue screening should be interpreted as relative values for comparison; the objective of this model is to identify critical locations that require intermediate or detailed local models. A detailed discussion is given in Paper E.

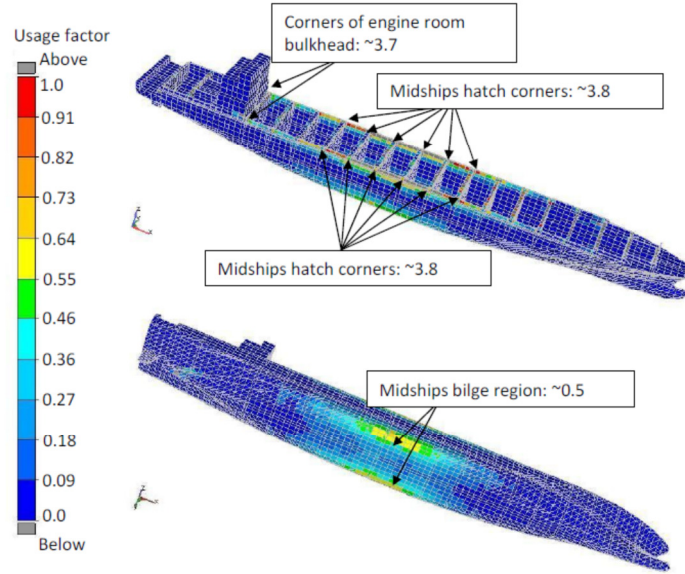


Fig. 7.3: Critical regions in the ship with maximum usage factors located in the midship hatch corners (3.8), engine room bulkhead (3.7) and bilge region (0.5).

7.3.2 Time-domain fatigue life prediction of the side-shell longitudinals

The side longitudinals illustrated in Fig. 5.3 are utilised to demonstrate the proposed time-domain fatigue life prediction procedure. The detailed description of this calculation procedure is presented in Paper C. Using this method, the accumulated fatigue damage is calculated as a summation of the partial fatigue damages (D_i) multiplied by their respective probabilities of occurrence (p_i) for all sea states encountered during the ship's lifetime:

$$D_{total} = \sum_i p_i D_i \quad (7.5)$$

A representative wave scatter diagram was designed for the case study container vessel and its route. This simplified wave scatter diagram is presented in Table 7.4 and is based on 20 encountered sea states, the corresponding probabilities of occurrence (p_i), and the ship speed. These sea states are based on the standard wave scatter diagram for the North Atlantic (IACS, 2001). The ship speed for each encountered wave height is presented in Table 7.4. The speed reduction is related to the encountered wave height because of added resistance in higher waves and also because speed reduction is often made voluntarily by the captain, who is responsible for comfort and cargo safety. The reduced speeds are determined based on onboard observations of the case study vessel and linearly extrapolated for higher wave heights when the measurements are not available.

Table 7.4: Simplified wave scatter diagram used in the long-term fatigue assessment in the time-domain.

<i>Block</i>	H_s [m]	T_p [s]	p_i [%]	U [m/s]	<i>Block</i>	H_s [m]	T_p [s]	p_i [%]	U [m/s]
#1	1.5	10.6	30.36	11.8	#11	5.5	16.3	3.29	8.2
#2	1.5	13.4	9.36	11.8	#12	5.5	19.1	0.65	8.2
#3	1.5	16.3	0.69	11.8	#13	7.5	10.6	0.26	6.2
#4	1.5	19.1	0.08	11.8	#14	7.5	13.4	2.39	6.2
#5	3.5	10.6	12.69	9.8	#15	7.5	16.3	2.12	6.2
#6	3.5	13.4	20.02	9.8	#16	7.5	19.1	0.50	6.2
#7	3.5	16.3	4.42	9.8	#17	9.5	10.6	0.08	4.1
#8	3.5	19.1	0.39	9.8	#18	9.5	13.4	0.46	4.1
#9	5.5	10.6	2.01	8.2	#19	9.5	16.3	0.66	4.1
#10	5.5	13.4	9.35	8.2	#20	9.5	19.1	0.25	4.1

The heading of the ship in relation to the wave encounter direction is another important factor that significantly influences fatigue damage. To achieve an accurate fatigue estimate, the fatigue damage must be calculated for each wave heading. In this thesis, the variation in heading is addressed by using eight representative heading angles. The oblique waves from the windward side are defined by a positive heading. Accordingly, the leeward oblique waves are defined by negative heading values (see Table 7.5). The headings are assumed to have variable occurrence probabilities, i.e., head seas and following seas are encountered with a probability of 20%, whereas the oblique seas and beam seas are encountered with a probability of 10%, as presented in Table 7.5. This uneven occurrence probability of headings is due to the target vessel operating in the North Atlantic, where head seas and following seas are more common according to actual observations (Mao, 2010). The occurrence probabilities in Table 7.5 apply for all of the representative sea states in Table 7.4.

Table 7.5: Definition and occurrence probability of the headings.

	Bow sea leeward	Beam sea leeward	Quarter sea leeward	Follow- ing sea	Quarter sea windward	Beam sea windward	Bow sea windward	Head sea
Heading [°]	-135	-90	-45	0	45	90	135	180
p_b	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.2

20-min partial damages under various wave headings for the representative sea states are calculated separately according to the specific ship speed as presented in Table 7.4. For each sea state, partial fatigue damages for all heading angles are summed and multiplied by the occurrence probability of this specific sea state (p_i in Table 7.4). The partial damages are weighted with the heading probabilities (p_b in Table 7.5). A summation of all the partial damages for each heading yields the resultant 20-min accumulated fatigue damage D_{20min} for all representative sea states. See Paper C for overall results and detailed description.

The total accumulated damage for a target service life of 20 years, $D_{20years}$, is obtained from Eq. (7.6), assuming that 85% of the ship's lifetime is at sea. For the side longitudinals, $D_{20years}=2.99$, corresponding to a fatigue life of 6.7 years. The overall results are provided in Paper C. As comparison, a fatigue analysis was also carried out with the spectral approach, resulting in a similar fatigue life (7.1 years). However, the time-domain procedure considers

more factors in the simulations, such as the nonlinear effects in loads, speed reductions, and variations in encountered wave headings. Thus, this result using the time-domain-based procedure should be considered more realistic than the one using the spectral method. However, both methods predict fatigue lives significantly shorter than the target service life, which may imply that the current fatigue design practice for side-shell structures should be re-examined.

$$D_{20 \text{ years}} = D_{20 \text{ min}} \cdot (20 \times 365 \times 24 \times 3 \times 0.85) \quad (7.6)$$

7.4 Fatigue routing

7.4.1 Application of a ship-routing fatigue model

Similar to ship-routing designs for expected times of arrival and fuel consumption, it is possible to use ship route planning to reduce fatigue damage accumulation. To plan fatigue routing and/or fatigue accumulation monitoring, a fatigue model and analysis procedure was proposed (Mao et al., 2010) where the theoretical development of the fatigue assessment methodology has been described in detail. The model is based on a narrow-band approximation. For a stationary sea state of length T , it is a function of the ship speed U , the heading angle θ , the encountered significant wave height H_s , the material parameter α , and the zero up-crossing frequency of stress f_z :

$$D \approx \frac{0.47}{\alpha} T f_z(U, \theta) [C(U, \theta) H_s]^3 \quad (7.7)$$

In a stationary sea state, the factor C is used to describe the proportional relationship between the standard deviation of the ship's response and the encountered significant wave height; it transfers H_s into significant stress. Furthermore, we propose to approximate f_z , the zero up-crossing frequency of stress, by the encountered wave frequency. The details on deriving C and f_z are provided in Paper B and in Mao et al. (2010). Through this method, the fatigue analysis of the model only requires information of the significant wave height H_s and the operational profiles U and θ , which can be easily accessed from the ship.

Paper B presents an application of a ship-routing fatigue model with case studies of real-life container vessels. The aforementioned fatigue model was used to demonstrate the possibility and benefits of ship route planning that leads to a reduction in fatigue damage accumulation. The two case study container ships are used to demonstrate the fatigue application in ship routing using the proposed fatigue model. The measurement data of the 2800TEU during the first six months of 2008 were utilised in this study. The ship speed was obtained from the onboard measurements, whereas the encountered wave environments and heading angles were determined from the hindcast data. Although these voyages were measured on the 2800TEU vessel, fatigue damages were also calculated for the 4400TEU ship, assuming that the 4400TEU vessel followed the same routes and had the same operational features. See Paper B for a detailed description of these passage routes.

Based on the measured passages of the 2800TEU ship, seven routes from Europe to North America are designated for possible sailings. Furthermore, based on experience and the measurement data, a series of voyages are designed with the assumption that each of the voyages begins at an assumed time. The assumed voyages are listed in Table 7.6. Furthermore, the ship is assumed to follow the designated routes at the measured speed for each voyage. With these parameters, the encountered wave environment and heading angle at

any specific time and location can be determined by the hindcast data. Combined with the speed specified by the measurements, the fatigue damage can be calculated from Eq. (7.7).

Table 7.6: Departure time of different voyages for both winter and summer sailing.

Voyage name	Departure day	Departure time
Voy0101	1 January	00:00
Voy0110	10 January	00:00
Voy0120	20 January	00:00
Voy0701	1 July	00:00
Voy1201	1 December	00:00
Voy1210	10 December	00:00
Voy1220	20 December	00:00

The computed fatigue damages in all six winter voyages with 42 possible routes are presented in Fig. 7.4. The influence of the voyage period was found to be the decisive factor regarding fatigue damage. For example, in comparing Voy0101 (departure on 1 January) and voyage 2 (departure on 10 January), the 10-day difference in departure time led to a 65% decrease in fatigue damage on average among all possible routes. Furthermore, the calculated fatigue damage was found to depend strongly on the selected ship. For most voyages, the fatigue damage can be decreased by up to 50% by selecting the optimised route. Additional results and discussions are offered in Paper B.

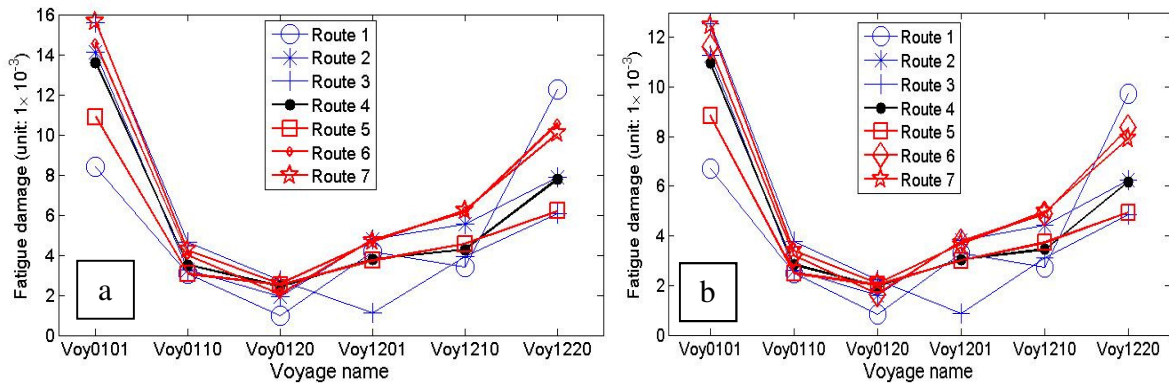


Fig. 7.4: Fatigue damage accumulated in voyages from Europe to North America: (a) results for the 2800TEU container vessel and (b) results for the 4400TEU container vessel.

7.4.2 Routing tool – fatigue damage vs. heading and speed

During a ship's operating conditions, it would be of great value to have a tool on the ship's bridge that indicates the current status in terms of the fatigue damage rate in a number of critical locations. It would also be interesting to know how the fatigue damage rate in these locations changes according to changes in the speed or heading of the vessel. The torsion-induced fatigue must also be considered for container vessels. The investigation in Paper A contributes to the further development of a fatigue routing tool by providing knowledge of the fatigue contribution from horizontal bending and torsion for different heading angles and ship speeds. In addition, Fig. 7.5 presents polar diagrams of the 20 min accumulated fatigue damage on the deck amidships and in the bilge amidships (see Fig. 6.2 for the locations) of the 4400TEU ship, respectively. The significant wave heights are $H_s=5$ m. It was assumed that the probabilities of wave headings are symmetrical with respect to the ship's course, i.e., the chances that waves come from the port and starboard side are identical. The diagrams

illustrate how a change of course or a change in speed (radial direction) would change the accumulation of fatigue damage. See Paper A for a detailed description of the simulation setup, results, and discussion.

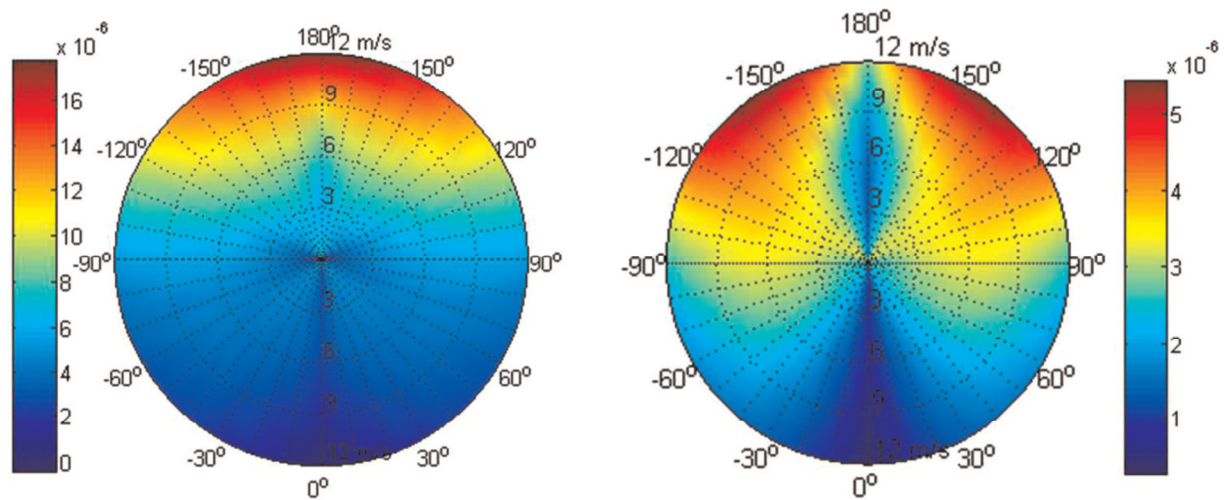


Fig. 7.5: Polar diagram of the accumulated fatigue damage on the deck (to the left) and the bilge (to the right) areas amidships. Fatigue damage is computed using the total longitudinal stress obtained from the ship responses of the 4400TEU ship.

8 Conclusions

This doctoral thesis focuses on the development and improvement of a stress-based fatigue assessment methodology for ship structures. A practical time-domain procedure is proposed. With this procedure, more sophisticated numerical tools can be utilised to consider more realistic sea and operational conditions, thus enabling an improved fatigue life prediction. Essential influencing factors are identified and quantified with the purpose of assessing the uncertainties associated with fatigue analysis procedures. Although this particular work concerns container vessels, it provides good insight into the direct calculation procedures of fatigue in general. The research results have been published in selected journals. The primary contributions of this work to the fatigue assessment of ship structures can be summarised as follows:

- The proposed time-domain procedure provides reasonable and conservative fatigue life estimations in comparison with the fatigue methodologies in widespread use. The advantage of the proposed time-domain approach is its flexibility in utilising more sophisticated numerical tools in accounting for realistic sea conditions and actual operational profiles, leading to improved accuracy in fatigue assessment.
- The influences of time record length and timestep length are rather insignificant to the time-domain procedure. In considering the balance between engineering accuracy and computational effort, timesteps of 0.1 s for hydrodynamic simulations and 0.5 s for FE analyses are used for the investigated cases. For short-term fatigue damage estimations, a time history of 20 min is generally sufficient for a single realisation, although more realisations are necessary when investigating the uncertainties associated with numerical analysis.
- Nonlinear wave loads were investigated with respect to fatigue for deck longitudinals and side-shell structures below the still waterline using the global ship models. The fatigue results indicate that variations exist between the linear and nonlinear algorithms. The difference increases with increasing wave heights but remains relatively small for the case study vessel. The sea pressure load applied on the side longitudinals must be further assessed through local models.
- A correct quantification of local stress is crucial for improving fatigue calculation accuracy. A new concept of the LSF is introduced to directly obtain the local stress from the global nominal stress record for fatigue damage calculations. Moreover, the LSF depends on not only the structural configuration but also the applied load, including the load level and load type. Further investigation of LSF should be undertaken.
- The nonlinear structural FE analysis of the side-shell structural details confirmed that the highest accumulation of equivalent plastic strain is located in the cut-out in the outer shell of the model. However, the plastic strain around this region is fairly low, and the rate of accumulation during cyclic loading decreased for every loading cycle. A strain-based fatigue assessment is unnecessary for the studied case, and a stress-based approach can be used for the fatigue assessment of the studied structural details.

- Various measurements of the wave environment lead to significant variations in predicted fatigue damages. Furthermore, the description of wave spectrum and the assumption of wave spreading are important sources of uncertainty in fatigue life prediction.
- The comparison of various fatigue analysis approaches illustrates that a narrow band approximation approach gives similar fatigue estimation as the time-domain approach; the strip theory code provides agreeable fatigue estimation under relatively small waves but becomes less reliable for larger waves, while this conclusion must be viewed with caution because it was only verified for structural members that were not subjected to sea pressures.
- Based on a comparative study, the method where the stress is derived from a FE analysis provides reasonable and conservative fatigue damage and is thus recommended. Beam theory may replace FE analysis to determine the stress for fatigue calculation if the deck longitudinals of container ships are of concern. This finding is important because considerable efforts are required in the FE modelling of a ship's hull.
- In the case study of ship fatigue routing, it was determined that up to two thirds of fatigue damages can be reduced by routing. Fatigue damage depends largely on the vessel's route, for which the encountered sea conditions and operational profiles can significantly differ.
- Wave-induced warping stresses play an important role in the hull girder stresses in container vessels. The results demonstrate that warping stress is typically correlated with stress due to horizontal bending. In the bilge, the stresses are nearly in phase and are thus superposed onto the total stress. On the deck, however, the stresses are out of phase, which leads to counteraction and implies that the stress caused by vertical bending dominates the deck longitudinals.
- In general, the greatest fatigue damage for deck longitudinals of container ships occurs in head seas, whereas in the bilge areas, the greatest fatigue damage is related to oblique seas. Based on these findings, a polar diagram of ship speed and heading angle changes was designed and proven useful for ship routing with respect to fatigue damage monitoring in a ship's hull.

9 Future work

The work presented in this thesis spans over several scientific disciplines and covers most essential issues in ship fatigue assessment. Nevertheless, certain factors deserve further investigation, and there are other important issues that have been omitted from the scope of this thesis that should be addressed. Recommendations for the possible continuation of the current work are suggested below.

Local stress factor

A correct quantification of local stress is crucial for improving fatigue calculation accuracy. The LSF was introduced to obtain the local fatigue stress directly from the global nominal stress. However, it was found that the LSF depends on not only the structural configuration but also the applied load, including the load level and load type. Thus, a LSF cannot simply be used in similar structural details at other locations of the hull. This problem cannot be addressed by defining different SCF for different load components and superpositioning local stress components because a correct combination of load components under realistic loading and operational conditions appear unlikely, particularly for structural members subjected to complex loads (such as the side-shell longitudinals). However, it is expected that a LSF database can be established with certain effort when essential loading and operational conditions are considered.

Efficient time-domain method by incorporating beam theory

The proposed time-domain fatigue assessment procedure is believed to improve the accuracy of fatigue life estimation. The drawback of the procedure is that the time-domain approach requires intensive computational effort compared to the existing frequency-domain approaches due to the time-consuming FE analyses for large structures, such as an entire ship's hull. This disadvantage can be partially addressed by incorporating beam theory in determining the global nominal stress so that the FE analyses can be significantly reduced. The parameters required by beam theory such as the section modulus can be constructed through matching stress records from a FE analysis with corresponding sectional loads from hydrodynamic simulations. The preliminary outcome is promising, and one paper interpreting this methodology is already in process.

Whipping and springing

In the scope of this thesis, wave loads and ship responses were confined to the wave frequency. The ship was considered a rigid body in the structural analysis to determine the deflection and stress in the structure. However, in reality, a ship is flexible and may vibrate with various excitations. Wave-induced vibrations increase the stress level in a ship's hull and introduce fatigue damages that are also caused by wave loads in higher frequencies. In recent years, a number of papers have been published about wave-induced vibration in the scope of hydroelasticity that consider both extreme responses and aspects of fatigue. Although significant progress in knowledge and theoretical modelling has been achieved, a general vision about how wave-induced vibrations contribute to total wave-induced fatigue is still under discussion. Current methodologies for wave-induced vibrations rely to a great extent on full-scale measurements and model tests. A practical numerical procedure that uses direct calculations of wave loads and ship dynamic responses accounting for vibrations would be desirable and regarded as a significant contribution to the research of ship structure fatigue.

Multiaxial fatigue

Multiaxial fatigue behaviour is complex. For ship structures that feature welded plating, the stress multiaxiality is typically represented by the biaxial forces applied to the load-carrying fillet and butt welds. Various fatigue equivalent stresses and different fatigue check criteria are recommended in guidelines from classification societies and other organisations. In this thesis, the biaxial stress state of a ship's structural detail is treated with the approach of reference principal stress, as indicated in Section 3.4. However, there is no evidence that this approach is better than others; in fact, no generally applicable multiaxial fatigue criterion exists (Stambaugh et al., 1990). A recent benchmark study from ISSC (2012) used typical ship structures to identify the methodology most appropriate for fatigue assessment of welded joints in a state of biaxial stress. Although the case studies were of simple scenarios and such influencing factors as manufacturing misalignment were neglected, the fatigue estimation results exhibited significant scatter; it was impossible to judge whether the structural details under study met the fatigue requirement. This benchmark study highlighted the necessity of further investigation of the multiaxial fatigue of ship structures.

Fracture mechanics

The S-N method is a simple and efficient but cannot be applied to predict the residual fatigue life for vessels with cracked structural members. However, to avoid potentially hazardous situations, it is essential to assess fatigue crack propagation so that appropriate countermeasures can be adopted systematically through proper inspection and maintenance procedures. A fracture mechanics approach should be implemented, and the time-domain loading record can be used as input. For a given loading history, the accumulated crack length can be calculated on a cycle-by-cycle basis. The realistic loading at the structural details, such as the combined loading from various amplitudes and phases, the mean stress effect and size effect can all be included in fatigue crack propagation analysis.

References

ABAQUS, 2011. *Abaqus/CAE User's Manual Version 6.11*. Dassault Systèmes.

ABS, 2004. *Guidance Notes on Spectral-based Fatigue Analysis for Vessels (Updated 2009)*. American Bureau of Shipping.

ABS, 2011. *Rules for Building and Classing Steel Vessels, Part 5C*. American Bureau of Shipping.

Agerskov, H., 2000. *Fatigue in steel structures under random loading*. Journal of Constructional Steel Research **53**(3): 283-305.

Baxevani, A., Caires, S., Rychlik, I., 2009. *Spatio-temporal statistical modelling of significant wave height*. Environmetrics **20**(1): 14-31.

Beck, R.S., Dalzell, J., Faltinsen, O., M., R.A., 2009. *Motions in waves*, in: Paulding, J.R. (Ed.), Principles of Naval Architecture: The Series. Society of Naval Architects and Marine Engineers, Jersey City, NJ.

Bendat, J.S., Corporation, M.A., Aeronautics, U.S.N., Administration, S., 1964. *Probability functions for random responses: prediction for peaks, fatigue damage, and catastrophic failures*. National Aeronautics and Space Administration.

Berstad, A.J., 1999. *Calculation of fatigue damage in ship structures, Doctoral thesis*. Norwegian University of Science and Technology, Trondheim; Norway.

Bitner-Gregersen, E.M., Cramer, E.H., Korbijn, F., 1995. *Environmental description for long-term load response of ship structures*, ISOPE 95, 5th Intl Offshore & Polar Engng Conf; 11-16 June 1995; The Hague, The Netherlands.

BV, 2008a. *Guidance Note NI 532, Guidelines for Structural Analysis of Container Ships*. Bureau Veritas.

BV, 2008b. *Guidance Note NI 539, Spectral Fatigue Analysis methodology for ships and offshore units*. Bureau Veritas.

Cariou, A., Jancart, F., 2003. *Influence of modelling on calculated sea loads on ships*. Marine Structures **16**(2): 149-173.

Chiou, J.-W., Chen, Y.-K., 1985. *Fatigue prediction analysis validation from SL-7 hatch corner strain data, SSC report 338*. Ship structure committee.

ClassNK, 1998. *Comprehensive damage review of 2nd generation of VLCCs*, ClassNK Casualty Review. Nippon Kaiji Kyokai.

ClassNK, 2003. *Guidelines for Container Carrier Structures*. Nippon Kaiji Kyokai.

Cui, W., 2002. *A state-of-the-art review on fatigue life prediction methods for metal structures*. Journal of Marine Science and Technology **7**(1): 43-56.

Dee, D.P., Uppala, S.M., Simmons, A.J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M.A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A.C.M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A.J., Haimberger, L., Healy, S.B., Hersbach, H., Hólm, E.V., Isaksen, L., Kållberg, P., Köhler, M., Matricardi, M., McNally, A.P., Monge-Sanz, B.M., Morcrette, J.J., Park, B.K., Peubey, C., de Rosnay, P., Tavolato, C., Thépaut, J.N., Vitart, F., 2011. *The ERA-Interim reanalysis: configuration and performance of the data assimilation system*. Quarterly Journal of the Royal Meteorological Society **137**(656): 553-597.

DNV, 1993. *SESAM User Manual WAVESHIP: Wave Loads on Slender Structures*. version 6.1. Det Norske Veritas, Høvik, Norway.

DNV, 2005. *'Hull Monitoring Systems', Rules for classification of Ships/High speed, Light Craft and Naval Surface Craft - Additional Class, Pt 6, Ch 11*, 2005. Det Norske Veritas.

DNV, 2006. *SESAM User Manual WASIM: Wave Loads on Vessels With Forward Speed*, version 3.4. Det Norske Veritas.

DNV, 2008. *SESAM User Manual SESTRAS: Superelement Structure Analysis*, version 8.3. Det Norske Veritas.

DNV, 2009a. *Classification Notes - No. 31.7: Strength Analysis of Hull Structures in Container Ships*. Det Norske Veritas.

DNV, 2009b. *SESAM User Manual STOFAT: Fatigue Damage Calculation of Welded Plates and Shells*, version 3.4. Det Norske Veritas.

DNV, 2010a. *Classification Note No. 30.7: Fatigue Assessment of Ship Structure*. Det Norske Veritas.

DNV, 2010b. *Classification Note No. 34.2: Plus - Extended Fatigue Analysis of Ship Details*. Det Norske Veritas.

DNV, 2010c. *Recommended Practice DNV-RP-C205: Environmental Conditions and Environmental Loads*. Det Norske Veritas.

DNV, 2011. *Classification Note No. 30.10: Extra High Strength Steel Material NV 47 for Hull Structural Application in Container Ships*. Det Norske Veritas.

DNV, 2013a. *Flyer: PLUS Analysis - Enhanced fatigue analysis of ship details*. Det norske Veritas.

DNV, 2013b. *SESAM URL* <http://www.dnv.com/services/software/products/sesam/>. Det Norske Veritas.

Dong, P., 2001. *A structural stress definition and numerical implementation for fatigue analysis of welded joints*. International Journal of Fatigue **23**(10): 865-876.

- Dowling, N.E., 2007. *Mechanical Behavior of Materials: Engineering Methods for Deformation, Fracture, and Fatigue*. Pearson Prentice Hall.
- Dowling, N.E., Calhoun, C.A., Arcari, A., 2009. *Mean stress effects in stress-life fatigue and the Walker equation*. *Fatigue & Fracture of Engineering Materials & Structures* **32**(3): 163-179.
- Drummen, I., Storhaug, G., Moan, T., 2008. *Experimental and numerical investigation of fatigue damage due to wave-induced vibrations in a containership in head seas*. *Journal of Marine Science and Technology* **13**(4): 428-445.
- Fatemi, A., Yang, L., 1998. *Cumulative fatigue damage and life prediction theories: A survey of the state of the art for homogeneous materials*. *International Journal of Fatigue* **20**(1): 9-34.
- Folsø, R., 1998. *Spectral fatigue damage calculation in the side shells of ships, with due account taken of the effect of alternating wet and dry areas*. *Marine Structures* **11**(7-8): 319-343.
- Fonseca, N., Guedes Soares, C., 1998. *Time-domain analysis of large-amplitude vertical ship motions and wave loads*. *Journal of Ship Research* **42**(2): 139-153.
- Fricke, W., 2003. *Fatigue analysis of welded joints: state of development*. *Marine Structures* **16**(3): 185-200.
- Fricke, W., Cui, W., Kierkegaard, H., Kihl, D., Koval, M., Mikkola, T., Parmentier, G., Toyosada, M., Yoon, J.H., 2002. *Comparative fatigue strength assessment of a structural detail in a containership using various approaches of classification societies*. *Marine Structures* **15**(1): 1-13.
- Fricke, W., Kahl, A., 2005. *Comparison of different structural stress approaches for fatigue assessment of welded ship structures*. *Marine Structures* **18**(7-8): 473-488.
- Fricke, W., Paetzold, H., 2010. *Full-scale fatigue tests of ship structures to validate the S-N approaches for fatigue strength assessment*. *Marine Structures* **23**(1): 115-130.
- Fricke, W., Paetzold, H., Rörup, J., 2010. *Fatigue strength of stiffener end connections: a comparative study of bulb flats and angle bars*, Proceedings of the 11th International Symposium on Practical Design of Ships and Other Floating Structures PRADS 2010; 2010 Sep 19-24; Rio de Janeiro, Brazil: COPPE/UFR
- Friis Hansen, P., Winterstein, S.R., 1995. *Fatigue damage in the side shells of ships*. *Marine Structures* **8**(6): 631-655.
- Fu, T., Fullerton, A., Hackett, E., Merrill, C., 2011. *Shipboard measurement of ocean waves*, Proceedings of the ASME Thirtieth International Conference on Ocean, Offshore and Arctic Engineering (OMAE 2011), Published on CD-ROMs, in Rotterdam, the Netherlands. June 19-24, 2011.
- Garbatov, Y., Rudan, S., Guedes Soares, C., 2010. *Fatigue assessment of welded trapezoidal joints of a very fast ferry subjected to combined load*. *Engineering Structures* **32**(3): 800-807.

GL, 2004. *Rules for Classification and Construction Chapter V-1-2; Guidelines for Fatigue Strength Analyses of Ship Structures*. Germanischer Lloyd.

GL, 2007. *Rules for Classification and Construction Chapter V-1-1: Guidelines for Global Strength Analysis of Container Ships*, Germanischer Lloyd Aktiengesellschaft.

GL, 2010. *Rules for Classification and Construction Chapter I-1-1; Ship technology Seagoing Ships Hull Structures*. Germanischer Lloyd.

Gu, X.K., Moan, T., 2002. *Long-term fatigue damage of ship structures under nonlinear wave loads*. Marine Technology **39**(2): 95-104.

Guedes Soares, C., Schellin, T., 1996. *Long term distribution of non-linear wave induced vertical bending moments on a containership*. Marine Structures **9**(3): 333-352.

Gurney, T.R., Institute of Materials, M., Mining, 2006. *Cumulative Damage of Welded Joints*. Woodhead Pub. and Maney Pub.

Heggelund, S.E., Storhaug, G., Choi, B.-K., 2011. *Full scale measurements of fatigue and extreme loading including whipping on an 8600TEU post panamax container vessel in the Asia to Europe trade*. ASME.

Hogben, N., Dacunha, N.M.C., Olliver, G.F., 1986. *Global Wave Statistics*. British Maritime Technology Ltd, Feltham, UK.

IACS, 2001. *Recommendation No.34: Standard Wave Data*. International Association of Classification Societies.

IACS, 2008. *Common Structural Rules for Double Hull Oil Tankers*. International Association of Classification Societies.

IACS, 2009. *Common Structural Rules for Bulk Carriers*. International Association of Classification Societies.

IACS, 2013. *Common Structural Rules for Bulk Carriers and Oil Tankers; External Release 1 APR 2013*. International Association of Classification Societies.

Iijima, K., Shigemi, T., Miyake, R., Kumano, A., 2004. *A practical method for torsional strength assessment of container ship structures*. Marine Structures **17**(5): 355-384.

Iijima, K., Yao, T., Moan, T., 2008. *Structural response of a ship in severe seas considering global hydroelastic vibrations*. Marine Structures **21**(4): 420-445.

IIW, 2008. *IIW document IIW-1823-07 ex XIII-2151r4-07/XV-1254r4-07: Recommendations for Fatigue Design of Welded Joints and Components*. International Institute of Welding.

IIW, 2010. *IIW document Recommendations for the Fatigue Assessment of Welded Structures by Notch Stress Analysis*. International Institute of Welding.

IMO, 2011. *Inclusion of regulations on energy efficiency for ships in MARPOL Annex VI. RESOLUTION MEPC.203(62)*. International Maritime Organization.

ISSC, 2009. *Proceedings of the 17th international ship and offshore structures congress: III.1 Ultimate Strength*, in: Jang, C.D., Hong, S.Y. (Eds.), International ship and offshore structures congress, Seoul, Korea.

ISSC, 2012. *Proceedings of the 18th international ship and offshore structures congress: III.2 Fatigue and Fracture*, in: Fricke, W., Bronsart, R. (Eds.), International ship and offshore structures congress, Rostock, Germany.

ITTC, 2008. *The seakeeping committee final report and recommendations to the 25th International Towing Tank Conference*.

Jensen, J.J., 2001. *Load and global response of ships*. Elsevier Science.

Jensen, J.J., Pedersen, P.T., 1979. *Wave-induced bending moments in ships – a quadratic theory*,. Trans RINA 121 (1979), pp. 151–165.

Jia, J., 2008. *An efficient nonlinear dynamic approach for calculating wave induced fatigue damage of offshore structures and its industrial applications for lifetime extension*. Applied Ocean Research **30**(3): 189-198.

Kahl, A., Menzel, W., 2008. *Full-scale measurements on a panamax containership*, Int. Symposium on Ship Repair Technology.

Kim, M.H., Kim, S.M., Kim, Y.N., Kim, S.G., Lee, K.E., Kim, G.R., 2009. *A comparative study for the fatigue assessment of a ship structure by use of hot spot stress and structural stress approaches*. Ocean Engineering **36**(14): 1067-1072.

Kinoshita, T., Kagemoto, H., Fujino, M., 1999. *A CFD application to wave-induced floating body dynamics*, Proceedings of the 7th International Conference on Numerical Ship Hydrodynamics, Nantes.

Lotsberg, I., Landet, E., 2005. *Fatigue capacity of side longitudinals in floating structures*. Marine Structures **18**(1): 25-42.

Lotsberg, I., Sigurdsson, G., 2006. *Hot spot stress S-N curve for fatigue analysis of plated structures*. Journal of Offshore Mechanics and Arctic Engineering-Transactions of the Asme **128**(4): 330-336.

Mao, W., 2010. *Fatigue Assessment and Extreme Response Prediction of Ship Structures*, Doctoral thesis. Chalmers University of Technology, Gothenburg; Sweden.

Mao, W., Ringsberg, J.W., Rychlik, I., Storhaug, G., 2009. *Comparison between a Fatigue Model for Voyage Planning and Measurements of a Container Vessel*. Omae 2009, Vol 2: 173-180.

Mao, W., Ringsberg, J.W., Rychlik, I., Storhaug, G., 2010. *Development of a fatigue model useful in ship routing design*. Journal of Ship Research **54**: 281-293.

Müller, L., 2003. *Explanation for cracks in large container ships (in German)*. Schiff & Hafen(12/2003): 30-31.

Nielsen, U.D., Jensen, J.J., 2011. *A novel approach for navigational guidance of ships using onboard monitoring systems*. Ocean Engineering **38**(2–3): 444-455.

Nielsen, U.D., Jensen, J.J., Pedersen, P.T., Ito, Y., 2011. *Onboard monitoring of fatigue damage rates in the hull girder*. Marine Structures **24**(2): 182-206.

Oka, M., Takami, T., Ogawa, Y., Takagi, K., 2011. *A study of design loads for fatigue strength utilizing direct calculation under real operational conditions*, .

Okada, T., Takeda, Y., Maeda, T., 2006. *On board measurement of stresses and deflections of a Post-Panamax containership and its feedback to rational design*. Marine Structures **19**(2–3): 141-172.

Olsen, A.S., Schrøter, C., Jensen, J.J., 2006. *Wave height distribution observed by ships in the North Atlantic*. Ships and Offshore Structures **1**(1): 1-12.

Pilkey, W.D., 1997. *Peterson's Stress Concentration Factors (2nd Edition)*. John Wiley & Sons.

Radaj, D., Sonsino, C.M., Fricke, W., 2006. *Fatigue Assessment of Welded Joints by Local Approaches*. Woodhead Pub.

Rodrigue, J.-P., 2013. *Global containerized maritime shipping: emergence and divergence* Seminar, Gothenburg, Sweden.

Salvesen, N., Tuck, E., Faltinsen, O., 1970. *Ship motions and sea loads*. Trans. SNAME **78**: 250-287.

Schijve, J., 2003. *Fatigue of structures and materials in the 20th century and the state of the art*. International Journal of Fatigue **25**(8): 679-702.

Schulte-Strathaus, R., Bea, R.G., 1991. *Fatigue Database Development and Analysis. Technical Report SMP 1-1, Structural Maintenance for New and Existing Ships* Department of Navel Architecture and Offshore Engineering, U.C.Berkeley, Berkeley, California.

Schütz, W., 1996. *A history of fatigue*. Engineering Fracture Mechanics **54**(2): 263-300.

Senjanović, I., Malenica, Š., Tomašević, S., 2009. *Hydroelasticity of large container ships*. Marine Structures **22**(2): 287-314.

Sharp, J.V., 1993. *Effect of uncertainties in predicted fatigue life on structural Reliability, Integrity of Offshore Structures--5*. Engineering Materials Advisory Services Ltd, 339 Halesowen Rd, Cradley Heath, Warley, West Midlands B64 6PH, UK, Glasgow; UK, pp. 215-234.

Singh, S., Sen, D., 2007. *A comparative linear and nonlinear ship motion study using 3-D time domain methods*. Ocean Engineering **34**(13): 1863-1881.

Soares, C.G., Weisse, R., Carretero, J.C., Alvarez, E., 2002. *A 40 years hindcast of wind, sea level and waves in European waters*, Proceedings of 21st International Conference on Offshore Mechanics and Arctic Engineering.

Song, M.-J., Kim, K.-H., Kim, Y., 2011. *Numerical analysis and validation of weakly nonlinear ship motions and structural loads on a modern containership*. Ocean Engineering **38**(1): 77-87.

SSC, 1985. *Case Study IX: MSC CARLA Complete Hull Failure in a Lengthened Container Vessel*; URL: http://www.shipstructure.org/case_studies/carla/. Ship Structure Committee.

Stambaugh, K.A., Jr., P.R.V.M., Munes, W.H., 1990. *Fatigue Performance Under Multi-Axial Loading In Marine Structures* Report Number: SSC-356. Ship Structure Committee.

Storhaug, G., Derbanne, Q., Choi, B.-K., Moan, T., Hermundstad, O.A., 2011. *Effect of whipping on fatigue and extreme loading of a 13000TEU container vessel in bow quartering seas based on model tests*. ASME.

Storhaug, G., Heggelund, S., 2008. *Measurements of wave induced vibrations and fatigue loading onboard two container vessels operating in harsh wave environment*. Transactions of RINA, Design & Operation of Container Vessels, London.

Storhaug, G., Moe, E., 2007. *Measurements of wave induced vibrations onboard a large container vessel operating in harsh environment*, 10th international symposium on practical design of ships and other floating structures, Houston; USA, pp. 64–72.

Storhaug, G., Moe, E., Piedras Lopes, T.A., 2007. *Whipping measurements onboard a midsize container vessel operating in the North Atlantic*, International Symposium on Ship Design and Construction, Shanghai, China; November 28–29, pp. 55-70.

Story, W.R., Fu, T.C., Hackett, E.E., 2011. *Radar measurements of ocean waves*, Proceedings of the ASME Thirtieth International Conference on Ocean, Offshore and Arctic Engineering (OMAE 2011), Published on CD-ROM in Rotterdam, the Netherlands. June 19-24, 2011.

Tran Nguyen, K., Garbatov, Y., Guedes Soares, C., 2012. *Fatigue damage assessment of corroded oil tanker details based on global and local stress approaches*. International Journal of Fatigue **43**(0): 197-206.

UNCTAD, 2012. *Review of Maritime Transport 2012*; . United Nations Conference on Trade and Development

WAFO-group, 2000. *WAFO - A Matlab Toolbox for Analysis of Random Waves and Loads - A Tutorial*; URL: <http://www.maths.lth.se/matstat/wafo>. Math. Stat., Center for Math. Sci., Lund Univ., Lund, Sweden.

Watanabe, I., Guedes Soares, C., 1999. *Comparative study on the time-domain analysis of non-linear ship motions and loads*. Marine Structures **12**(3): 153-170.

Wu, M., Hermundstad, O.A., 2002. *Time-domain simulation of wave-induced nonlinear motions and loads and its applications in ship design*. Marine Structures **15**(6): 561-597.

Yoneya, T., Kumano, A., Yamamoto, N., Shigemi, T., 1993. *Hull cracking of very large ship structures*. Integrity of Offshore Structures--5: 325-351.

Paper A

Paper B

Paper C

Paper D

Paper E